AD NUMBER

AD900885

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; Apr 1972. Other requests shall be referred to Air Force Avionics Laboratory, [RSP], Wright-Patterson AFB, OH 45433.

AUTHORITY

AFAL ltr, 25 Sep 1974

AFAL-TR-72-85

AD900885

REAL TIME IMPROVED COLOR IMAGE DISPLAY

PHILCO-FORD CORPORATION

AIR FORCE AVIONICS LABORATORY

ORIGINAL ... REPRODUCTIONS ...

Distribution limited to U.S. Government Agencies only, because this report covers test and evaluation of commercial products Apr 1972. Other requests of this document must be made through AFAL (RSP), Wright-Patterson AFB, OH 45433.

Air Force Avionics Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

REAL TIME IMPROVED COLOR IMAGE DISPLAY

PHILCO-FORD CORPORATION

Distribution limited to U.S. Government Agencies only, because this report covers test and evaluation of commercial products Apr 1972. Other requests of this document must be made through AFAL (RSP), Wright-Patterson AFB, OH 45433.

FOREWORD

This is the final report of Air Force Contract F33615-70-C-1417, "Real Time Improved Color Image Display". The period of performance covers a period between February 1970 and April 1972. This report was submitted for publication by the authors April 28, 1972.

The prime contractor for this project is Philco-Ford, 3939 Fabian Way, Palo Alto, California 94303. In the course of the contract, the following Philco personnel contributed to the design and study effort and served as co-authors of this report.

Harold Austefjord
Frederick Buhler
Alan deSchweinitz
Bryce Loucks
Eleazar Morales
Michael Parmett
Jonathan Roeloffs
Larry Shoenberger
Rodney Toone

The lens design was provided by Jan Hoogland.

This report was submitted April 28, 1972 and has been reviewed and approved:

ALBERT W. BERG
Chief
Recon Sensor Development Br
Recon & Surveillance Division
Air Force Avionics Laboratory

ABSTRACT

The work covered in this report was intended to explore preliminary designs and hardware implementation which would yield results to eventually provide a satisfactory design for a real-time improved color display.

The fundamental concept used in this work is not new. The sequential color approach used was first introduced by CBS over 30 years ago. The uniqueness of this approach involves the use of this concept along with projection optics to achieve significant advances in the display area of high resolution, color purity, and brightness while inherently having perfect registration.

The display development included the achievement of significant advances in the areas of optical design, CRT phosphor, specialized deflection, and video circuit designs. This report summarizes the results of these developments and subsequent evaluation. Information was derived, as a result of the test bed that was developed, which outlines a design capable of possible utilization as an airborne color display.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

SECTION 1

INTRODUCTION

The significance to the Air Force of this research and development is that it establishes an operating high-resolution color display, memory and interface which can be used to explore the advantages, benefits and limitations of color as a display tool for increasing operator effectiveness.

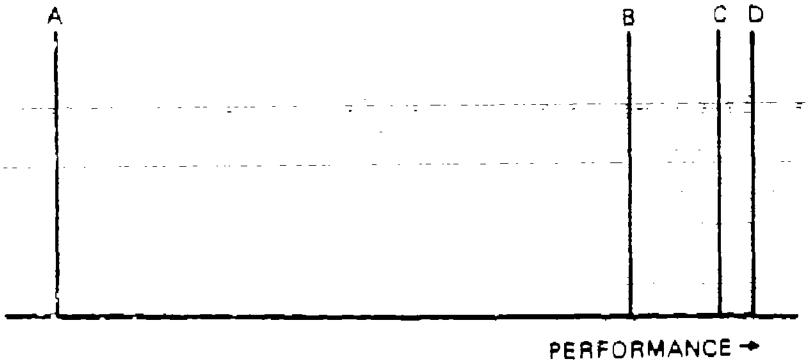
1.1 BACKGROUND

Ever since the real-time display of high-resolution color (multispectral) sensor imagery has been attempted it has been recognized that available color display techniques have been severely inadequate. This is especially true for the operation of a display in an airborne environment. The shadow mask CRT was indicated as the best "all around" color tube available, but its performance was severely limited and apparently had no chance for significant improvement. Over the years, several promising attempts have been made to exploit and develop other CRT techniques that up to that time had been only marginally successful.

In 1970, the Air Force Avionics Laboratory requested a study program for design and development of a tri-color display, the end product to be a design concept supported by experimental evidence and analysis.

1.2 OBJECTIVE

The objective of the study was to achieve improved color display capability through study, investigation, and experimental analysis of techniques developed as a result of this program.



Philco-Ford concurred with the Air Force Avionics Laboratory belief that a significantly improved color display system was needed. The belief was so strong that Philco-Ford has expended over three times the financial resources provided by the Air Force under the study contract.

In order to better understand this objective, an analogy must be made. If one were to relate the performance specification goals as a function of possible implemented displays, the qualitative relationship would be as depicted above.

The relationship would essentially be an inverse relationship of performance vs available or practical display implementations. Location A represents the color displays available at the initiation of the study. Included in this "A" group would be the present available shadow mask color monitors. The display developed for this study and subsequently evaluated is shown in position B. This sequential color display has improved resolution and high color purity. However, the data and subsequent analysis leads to recommendations which would enable improvement of the basic display, a display which would meet higher performance and is denoted by position C. This new display could be easily implemented by utilizing many of the components now developed. Position D represents a consolidation of all the desired goals of the sequential color display.

This report is a result of that display implementation and mass refresh memory design. It is hoped that this is a primary step in the goal of eventually obtaining even higher performance hardware.

Section 2.0 in this report describes a recommendation of a display which will be a major step toward achieveing the goal of a high-resolution color display.

To enable a more meaningful study, Philco-Ford committed capital funds to design and fabricate a high-resolution color test bed. This test bed contains special test equipment which produces a variety of color display patterns to help measure the display performance. Specifically, Philco-Ford developed or purchased the following major display items.

- Optics - An f/1.0 lens, considered state-of-the-art, which combines speed with high modulation transfer and transmission.

- Projection CRT - A high voltage, high efficiency composite phosphor tube using rare earth phosphers of high purity.

- Color Optics - A custom color wheel with over 90% transmission characteristics in each of the primaries.

- Color Test Generator - A sophisticated test simulator and MOS mass memory refresh system capable of 9,000,000 bits of memory storage.

This report summarizes the results of the subsequent development and evaluation. From the test bed developed comes the information and data which outline a design capable of possible utilization as an airborne color display.

1.3 DESCRIPTION OF EXPERIMENTAL DISPLAY UNIT

The laboratory model display unit was designed as a working breadboard with ease of modification in mind. Hinged walls are provided on all but the front panel. Figure 1 is a photograph of the unit with a side panel folded down. On the panel closest to the observer are the 50 kV and the test generator logic power supplies. On the back panel is the card cage for the test generator logic and display processing circuits. Under the card cage is the display's multivoltage power supply. On the opposite panel is the video projection amplifier adjacent to the CRT neck. The CRT assembly, motor color wheel, and lens are located on a rigid mount mounted to the display base. Not visible in the enclosed structure are two mirrors mounted to the front panel that complete the folded optics system.

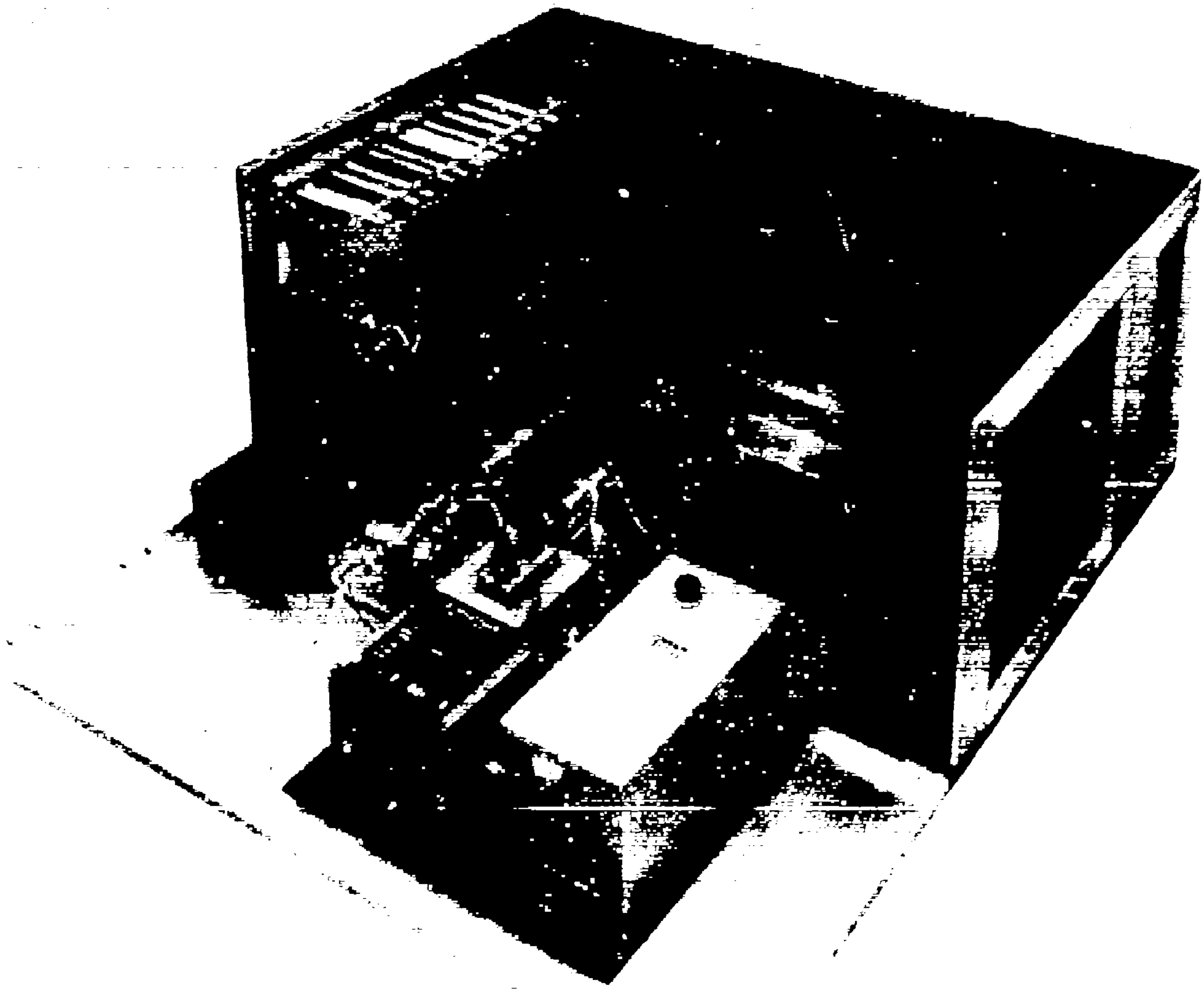


Figure 1 Display Unit with Side Panel Folded Down

Figure 2 shows the display with the panels in the normal position. This packaging scheme was utilized on the laboratory model where liberal access to all assemblies was required.

Figure 3 shows the rigid optical mount which contains the CRT mount, lens, and color wheel. The color wheel is located between the first and second element of the lens which can be seen in more detail on Figure 4. A control is provided on the CRT carriage to facilitiate mechanical focus. The display is exercised by the test generator. All controls are provided on the front control panel shown in Figure 5.

The most difficult hardware design areas were the color wheel and the lens. The difficulty in the color wheel was related to manufacturing process controls. The lens difficulty was one of basic design. Section 5 outlines the design in more detail. Other difficult design areas of the system involved the CRT phosphor selection, the video amplifier design and the deflection amplifier design. A complete discussion is detailed in Sections 4.0, 6.0, and 7.0 respectively.

ELECTRICAL OPERATION

In this sequential color system, two interlaced primary color fields comprise one primary color frame. Each color field is made up of perfectly registered sequential red, blue, and green horizontal scans. The interface generates the horizontal and vertical synchronizing pulses.

The first field is a primary full picture scan of every odd line while the second field is a similar full picture scan displaced by one horizontal line to provide even line interlacing. Since 1000 visible lines of resolution for each primary are utilized, 500 lines will be active on each interlaced field scan with 50.5 lines provided for each field retrace.

The primary parts of the display are the video circuits, color wheel control, vertical deflection, horizontal deflection, high-voltage power supply, focus and CRT protection circuits.

The video system accepts low level signals in the format outlined in Section 6.0 and conditions and amplifies the signal information to drive the projection CRT. Video bandwidth is approximately 60 MHz. Section 6.0 provides the discussion of the detailed design.

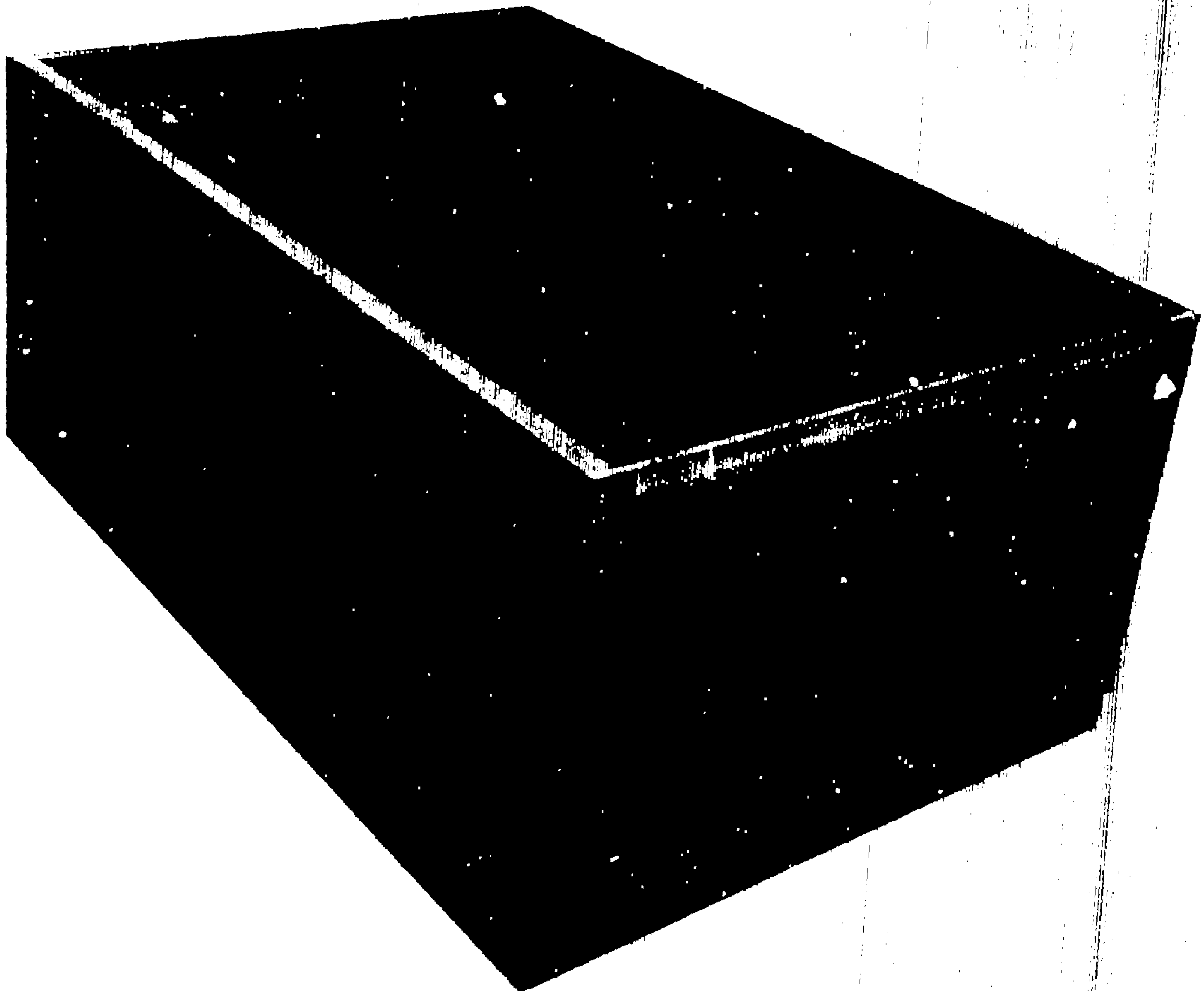


Figure 2 Display with the Panels in the Normal Position

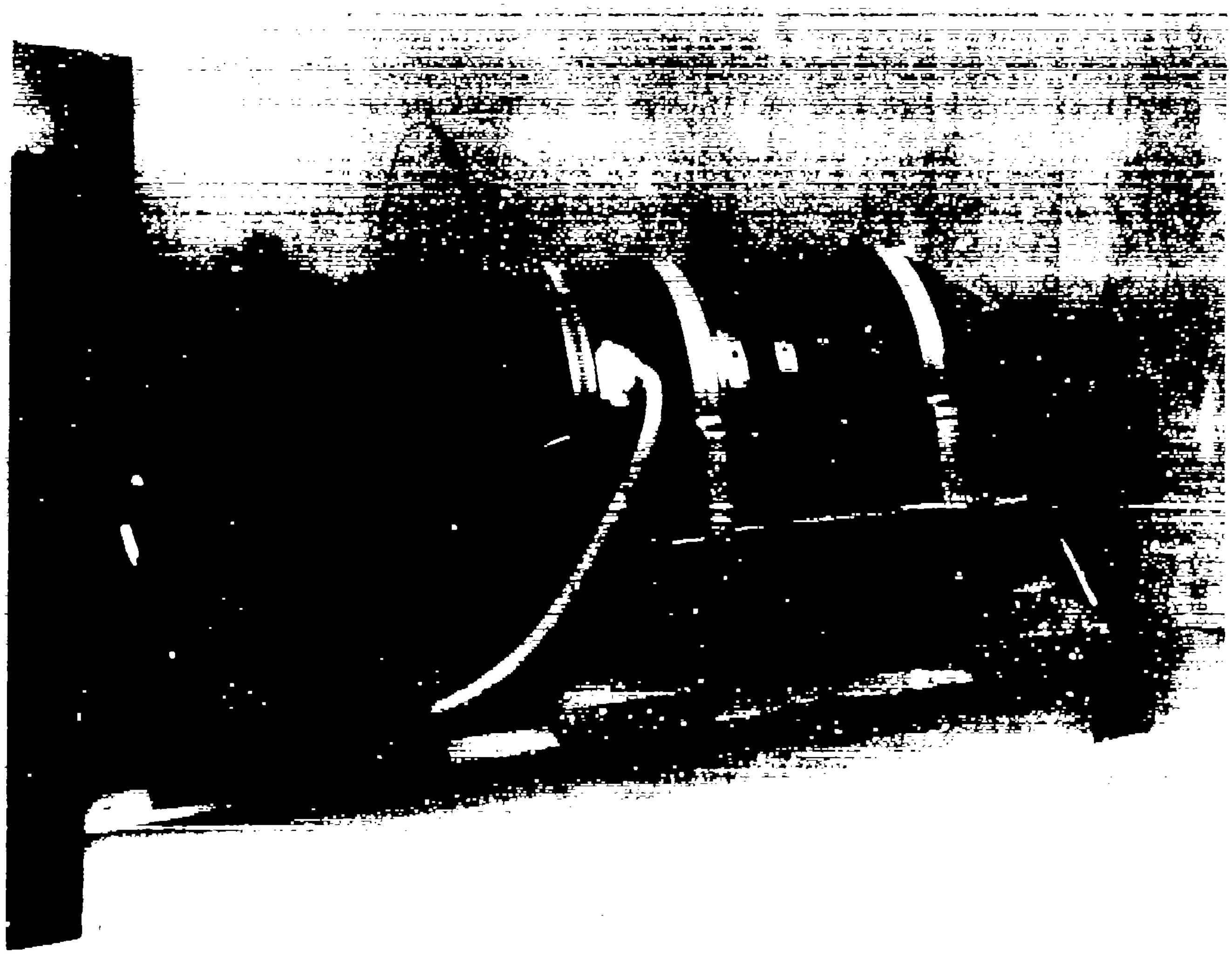


Figure 3 Rigid Optical Mount

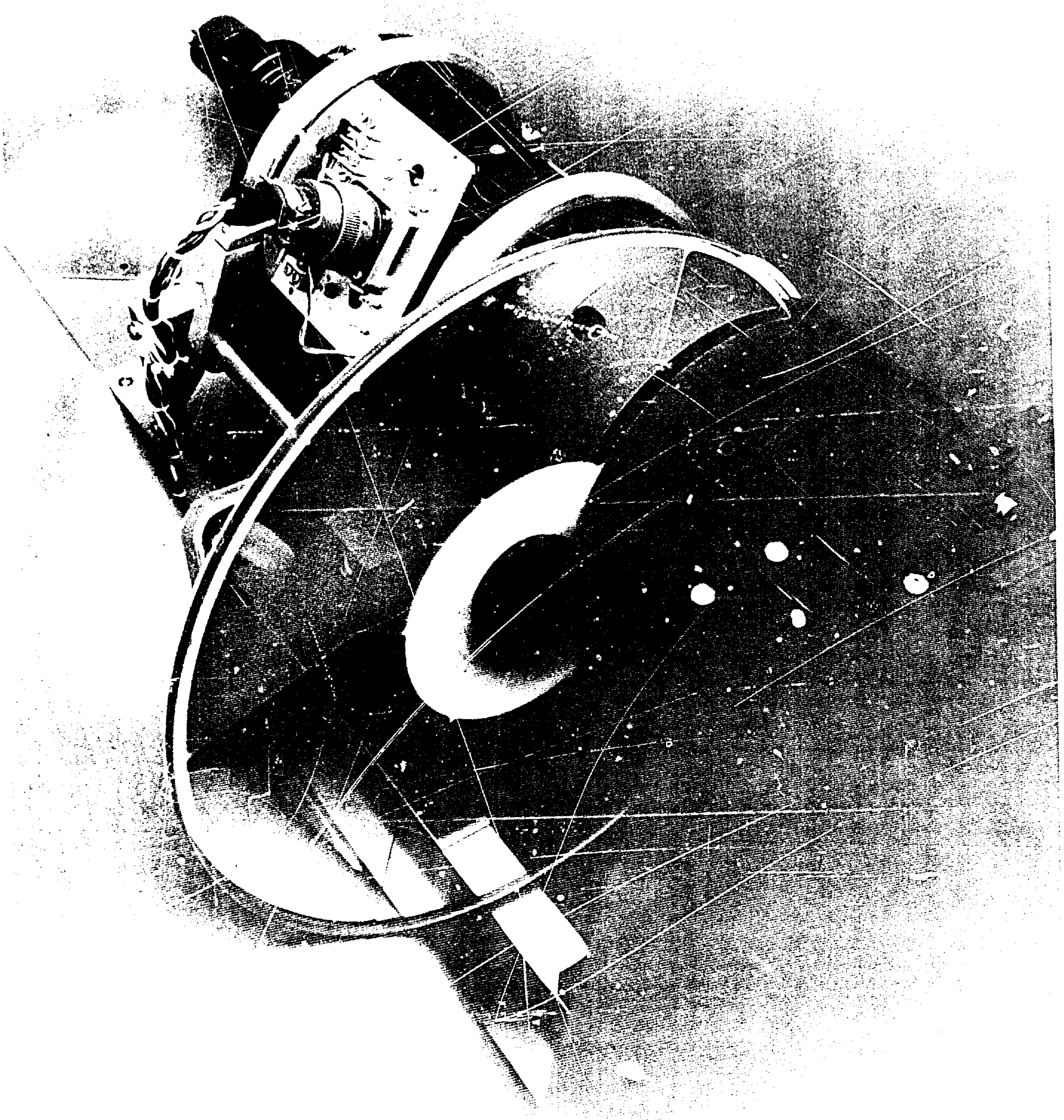


Figure 4 Color Wheel

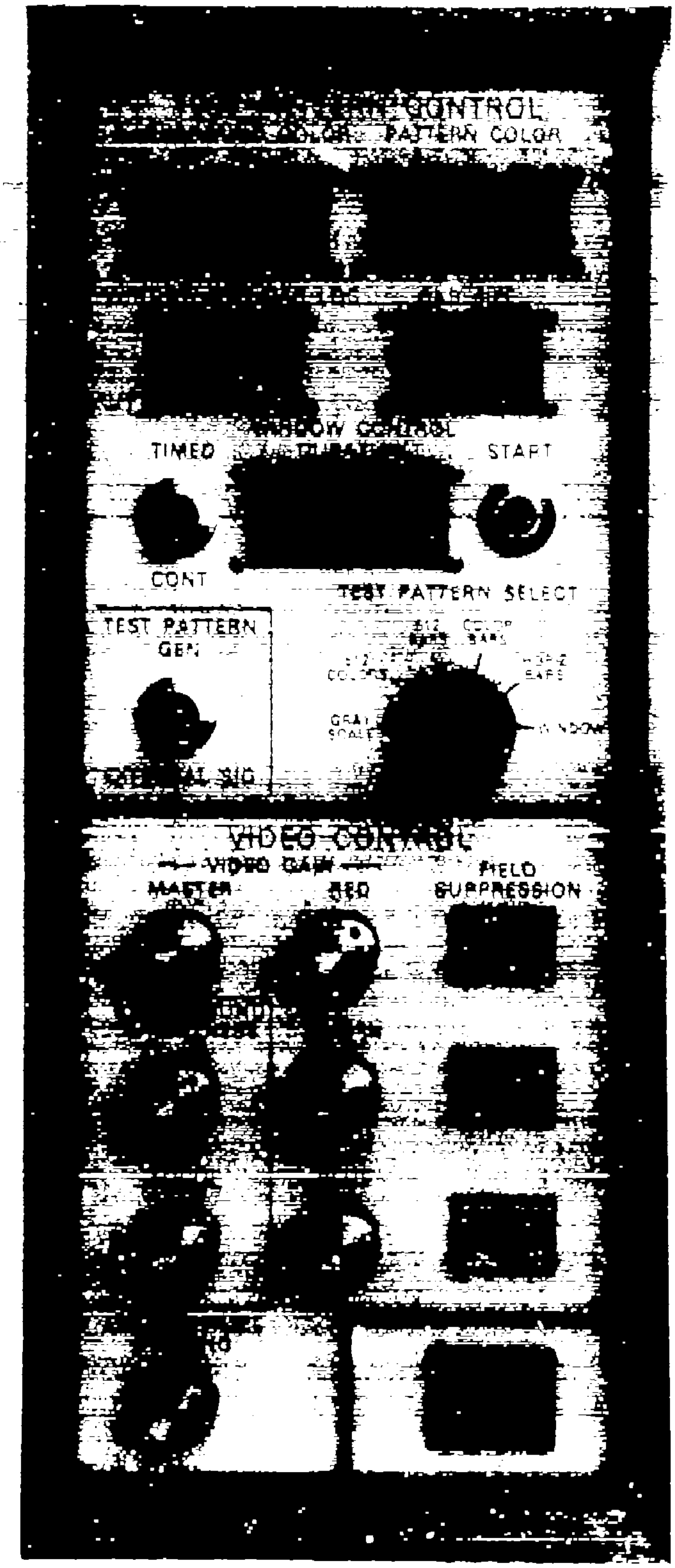


Figure 5 Front Control Panel

The color wheel control will sequence the color wheel rate and position to coincide with the vertical color field rate. Input is provided from the timing and sync generation. The design considerations are discussed in Sections 5.0 and 8.0.

The CRT provides a white high intensity output and operates with an accelerating voltage of 40,000 volts. The image is magnified by an F/1.0 lens and is projected onto a 14 inch square rear-projection screen via two optical folding mirrors. The selection and design of the lens was one of the most difficult tasks in the display development. A performance discussion as well as the final catalog design is given in Section 5.0.

The vertical deflection technique utilized is a standard ramp generator driving a linear amplifier. This amplifier design has been successfully proven in existing Philco-Ford tactical display equipment.

A difficult design problem existed for the horizontal deflection system. The scan speed must be approximately three times as fast as a conventional single color CRT Display of the same resolution. The result is a horizontal line period of about 10.0 microseconds, with 8.0 microseconds for the scan and 2.0 microseconds for the retrace. The difficulty existed because of the large energy transfer required to reset the deflection coil in the short retrace period. Section 7.0 outlines the design approach utilized in solving this problem.

Focus controls plus protection circuitry are also provided with the display unit. In addition to the detailed discussions of the individual color display design areas, a complete system circuit diagram is included in Appendix III.

1.4 EVALUATION OF LABORATORY DISPLAY UNIT

Paragraph 1.4.1 below lists the measured parameters, the specified requirements and the results obtained on the experimental display constructed by Philco-Ford to test the design concepts. In paragraph 1.4.2, the test methods and test set-ups are described for each of the parameters of paragraph 1.4.1. A discussion of the test results comparing them with the requirements is given in Section 2.0 along with a discussion of the ultimate performance attainable with this type of display, and specific improvements possible on the experimental display constructed by Philco-Ford.

1.4.1 Test Results

See Table 1-1.

1.4.2 Test Methods and Test Equipment Set-ups

The test methods and set-ups are described briefly for the tests itemized in Table I.

1.4.2.1 Screen Size. The screen size was measured with a standard ruler with 1/16" graduations.

1.4.2.2 Spatial Frequency Response. The spatial frequency response was measured using a Gamma model 2020 photometer readout and a microphotometer with a scanning eyepiece to read the light distribution in the horizontal and vertical directions.

To measure the modulation in the vertical axis, the odd or even field was blanked from the video creating a 500 line pair raster pattern which just filled the screen height. The Gamma model 700-10-62 scanning eye piece was then scanned vertically across the raster lines and the peak and valley readings noted. The modulation at this 500 line pair screen height spatial frequency was then calculated as:

$$\text{modulation } M = \frac{\text{Peak reading} - \text{Valley reading}}{\text{Peak reading}}$$

The test setup is shown schematically in Figure 6.

The divide-by-two circuit consisted of two pulse generators connected so as to divide the vertical sync by two and output an alternate field blanking pulse to the Ball Brothers Mark 81 multiplexer.

1.4.2.3 Brightness. The brightness* was measured with a Spectra model UB-1505 Brightness Spot photometer. The Spectra was calibrated before use with a Gamma Scientific model

* Note: In this report, the words "brightness" and "luminance" are used interchangeably to mean photometric luminance.

TABLE I

TEST RESULTS

ITEM	PARAMETER	REQUIREMENT	TEST RESULT ON EXPERIMENTAL DISPLAY
1	Screen Size	4.2.1.3 Screen Size: The screen size for presentation of imagery will be 14 by 14 inches.	14 inches by 14 inches
2	Spatial Frequency Response	4.2.1.4 Spatial Frequency Response: With a 1000 line sinusoidal signal input in both the vertical and horizontal dimensions, the modulation transfer factor (defined in 4.3.6) shall be 0.5 (i.e. 50% response) in both dimensions. In measuring the response in the direction perpendicular to the scanning lines, the input signal shall be registered with the scan lines.	At 1/2 Max. Brightness with Full Raster Center: 50% Vertical at 1000 TV lines 45% Horizontal at 1000 TV lines Corner: 15% Vertical at 1000 TV lines 10% Horizontal at 1000 TV lines
3	Brightness	4.2.1.5 Brightness: The maximum brightness of a balanced white output shall be at least 75 foot lamberts.	33 Footlamberts (Screen Gain = 2.8) x = 0.310; y = 0.350; (Ill "C" x = 0.310; y = 0.316)
4	Shading	4.2.1.7 Shading: The brightness at any point on the display screen shall not vary more than ± 5.0 percent from the average brightness when the display is set up for uniform brightness.	50% Falloff to Corners without Shading Modulation on Video
5	Gray Scale	4.2.1.8 Gray Scale: The display shall be capable of displaying 12 distinguishable gray shades. (Para. 4.3.4)	11 each $\sqrt{2}$ Gray Shades with 1 Footlambert Reference
6	Black and White Contrast Ratio	4.2.1.9 Black and White Contrast Ratio: The contrast ratio as defined in 4.3.5 shall be 75:1 when measured over concentric areas. The inner area will be 1 cm x 1 cm in size and darker than the outer area. The outer area will be 4 cm x 4 cm in size and have a brightness of 75 footlamberts or higher.	4.3:1 at 28 Footlamberts using a 1.3 cm x 1.3 cm dark area.
7	Color Gamut	4.2.1.11 Color Gamut: All colors within the triangle on the CIE Chromaticity Diagram whose apexes are approximated by the hues of 630 nanometers, 530 nanometers, and 470 nanometers. (See Figure 1.)	Chromaticity Coordinates (x, y); Dominant Hue Red 0.602 0.343 606 NM Green 0.240 0.704 540 NM Blue 0.148 0.135 476 NM
8	Purity	4.2.1.14 Purity: Purity will be at least 90 percent in all primary hues.	Red: 86%; Green: 89%; Blue: 80%
9	Color Brightness	4.2.1.15 Color Brightness: At least 15 footlamberts in each primary hue.	Red: 8.2 fL; Green: 46 fL; Blue: 3.8 fL
10	Color Brightness Shades	4.2.1.12 Color Brightness Shades: The display shall be capable of displaying seven distinguishable brightness levels (See 4.3.4) in each primary hue.	Red: 7 ea $\sqrt{2}$ shades Green: 12 ea $\sqrt{2}$ shades Blue: 5 ea $\sqrt{2}$ shades (1 fL Reference)
11	Color Linearity	4.2.1.13 Color Linearity: There will be no significant or perceptible change in hue with a change in brightness.	Red: No Change Green: Very Small Shift at Low Luminance Blue: No Change
12	Color Misregistration	4.2.1.16 Color Misregistration: Not to exceed 1/8 spatial cycle in the displayed image field.	Less than 1/8 Spatial Cycle at 1000 TV Lines
13	Flicker	4.2.1.6 Flicker: The display shall be flickerless when operated at a brightness of 75 foot lamberts.	Foveal: None Peripheral: Just Perceptible at 172 Hz Field Rate and 33 fL Highlight White.
14	Input Power	4.2.1.18 Input Power: 110 volts, 400 Hz and/or 28 volts DC Nominal Aircraft Power.	450 Watts, including power to built-in test generator
15	Size	4.2.1.19 Size: 12 cubic feet, or less.	12.67 cubic feet
16	Weight	4.2.1.20 Weight: 250 pounds, or less	311 pounds
17	Temperature	4.2.1.21 Temperature: Nominal ambient temperature for display operation will be 20° C	Operation satisfactory at 20°C

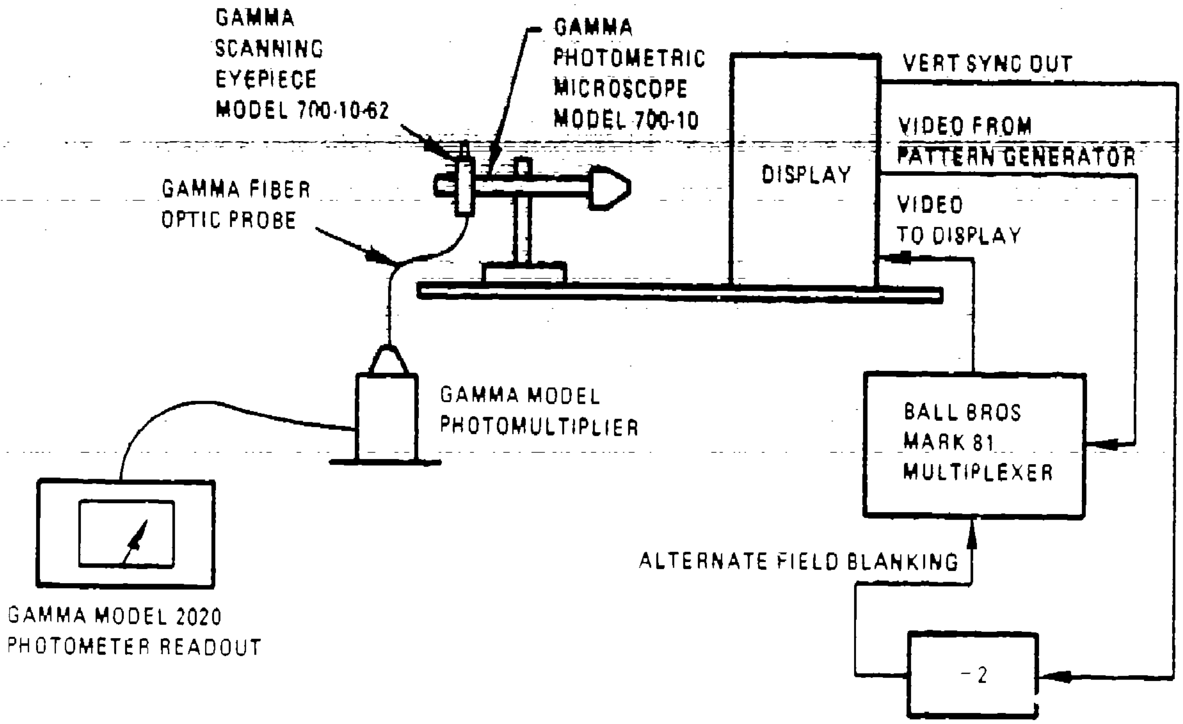


Figure 6 Test Set-up for Measuring Modulation

220-1 luminance standard head (100 footlamberts). When measuring the white highlight brightness, a Kollmorgen Tri-Rad Colorimeter was used to balance the light output to match Illuminant "C" ($x = 0.310 \pm 0.015$, $y = 0.316 \pm 0.015$).

A Spectra 5' SL-60 close-up lens was used with the Spectra model UB-1505 to examine a 0.3-inch diameter circle on the display screen.

1.4.2.4 Shading. The shading was measured using a calibrated Spectra model UB-1505 Brightness Spot photometer. The photometer was kept perpendicular to the screen and the luminances of the areas shown in Figure 7 were measured. The falloff in brightness was then calculated as

$$\text{falloff (in \%)} = \frac{\text{Center luminance} - \text{edge luminance} \times 100}{\text{Center luminance}}$$

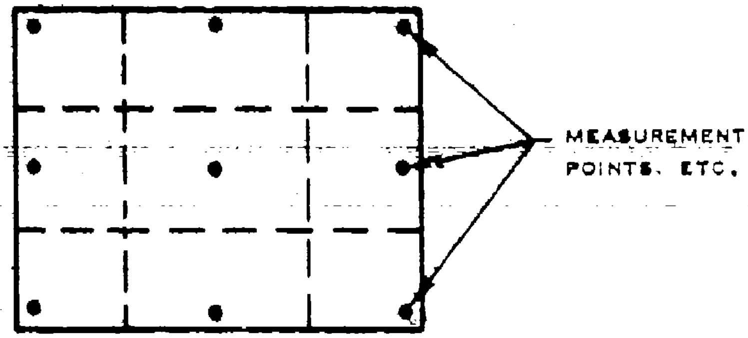


Figure 7 Measured Areas for Shading Test

1.4.2.5 Gray Scale. The number of gray shades is calculated by means of the following formula:

$$N = \frac{2\ \ell n(B_M / B_R)}{\ell n\ 2} - 1$$

where N = number $\sqrt{2}$ of shades

B_M = maximum measured brightness

B_R = reference minimum brightness of one footlambert (fL)

It should be noted that the number of gray shades obtainable increases to infinite if the refence brightness is taken as zero footlamberts. The reflection coefficient of the 2.5 gain screen is 14%. The maximum ambient usable for a minimum reference level of one footlamberts is 7 foot lamberts. If the general ambient is lower than 7 fL then it would be reasonable to select a lower reference minimum, thus increasing the number of gray shades.

1.4.2.6 Black and White Contrast Ratio. The black and white contrast ratio was measured according to the format specified by Wright-Patterson. The only exception was that the smallest dark window attainable with our test generator was 1.3 cm x 1.3 cm rather than 1cm x 1 cm. The brightness of the light and dark areas was measured with the Spectra UB-1505 photometer at the measurement points shown in Figure 8.

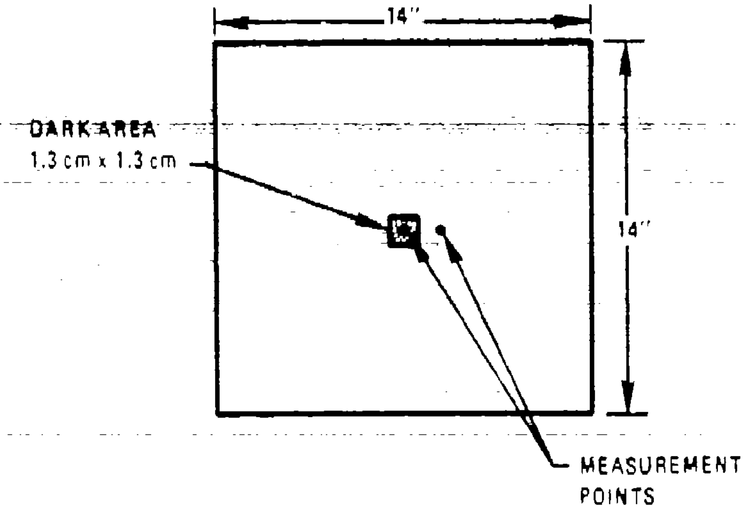


Figure 8 Measurement Points for Light-Dark Contrast Ratio

1.4.2.7 Color Gamut. The color gamut was determined by measuring the chromaticities of the three primary colors with a Kollmorgen Tri-Rad Colorimeter. These chromaticity coordinates were then plotted on a CIE chromaticity diagram. As shown in Figure 9, the color gamut includes all colors within the triangle formed by the red, green, and blue primaries.

1.4.2.8 Color Purity. The color purity is determined by the following formula:

$$P = \frac{D}{D_W} \times 100\%$$

Where D = length of a straight line on the CIE chromaticity diagram between the points which represent illuminant C, (white) and the color.

D_W = The length of a straight line between the points representing illuminant C (white) and the edge of the diagram and going through the point representing the unpure color.

The purity can also be more easily obtained by plotting the chromaticity coordinates of the three primaries on a chromaticity chart upon which are superimposed lines of constant purity. The purity is then easily and accurately obtained by inspection plus linear interpolation between the constant purity lines. Figure 10 shows the chart used by Philco-Ford with the primary coordinates marked on the chart.

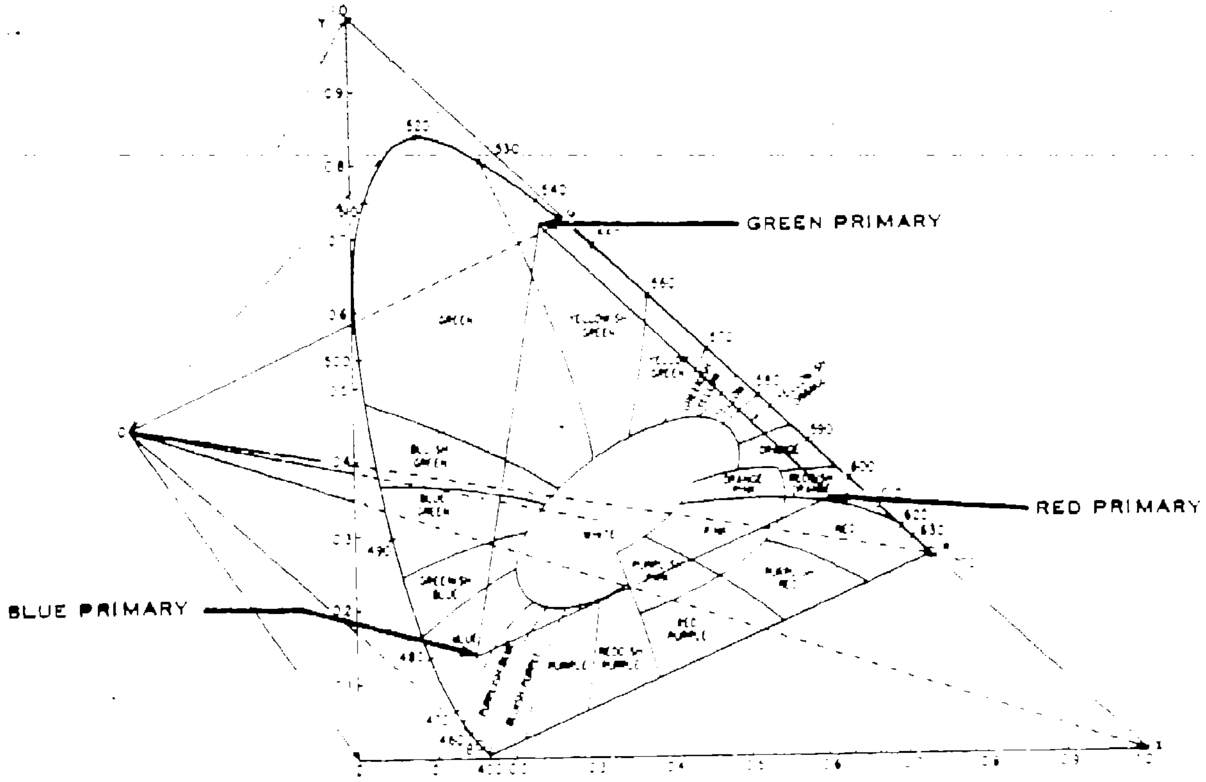


Figure 9 Color Solid and CIE Diagram

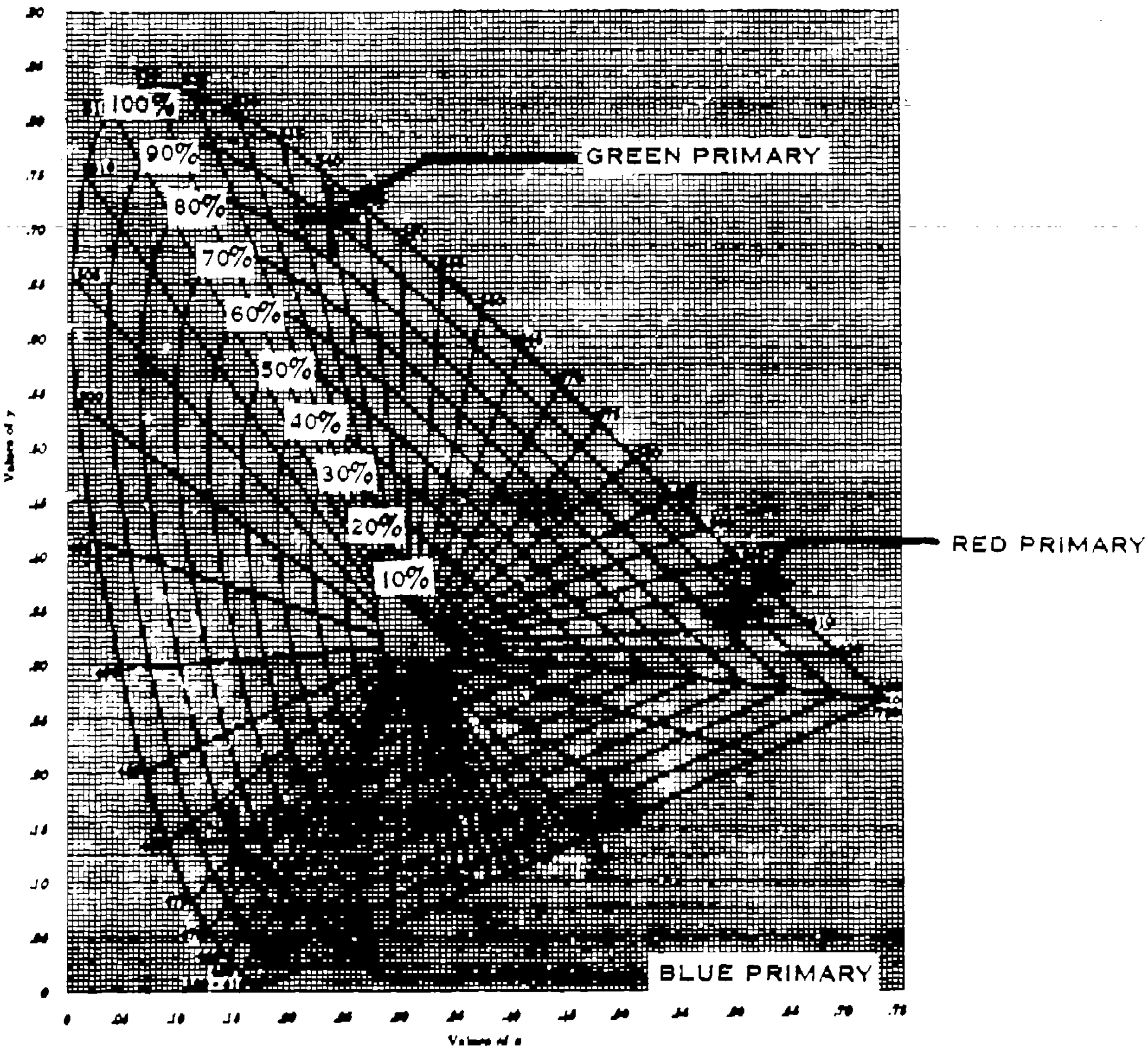


Figure 10 Chromaticity Diagram with Lines of Constant Dominant (and Complementary) Wavelengths and Curves of Constant Excitation Purity Based on Standard Source C as Achromatic Stimulus

1.4.2.9 Color Brightness. The color brightnesses were measured, again, using the Spectra Model UB-1505 Brightness Spot photometer. The three primary brightnesses were determined by suppressing two of the color fields and then measuring the color brightness of the unsuppressed color at the maximum video gain. The background level was set below the visible level in an ambient of less than 0.01 footlamberts.

1.4.2.10 Color Brightness Shades. The color brightness shades were determined by use of the same formula described in Paragraph 1.4.2.5.

$$N = \frac{2\,\ell n\,(B_M \,/\, B_R)}{\ell n\, 2} + 1$$

Where B_M = maximum color brightness

B_R = minimum reference brightness equal to footlambert

N = number of brightness shades

1.4.2.11 Color Linearity. The color linearity was measured by two methods. One method consisted of measuring the chromaticity coordinates at three brightnesses ranging from 1 footlambert to near the maximum in each primary. The second method was to visually observe the display while varying the brightness level and then attempt to judge whether the hue had varied with the brightness change.

Table II shows the data gathered for the various brightness levels. Note that a perceptible shift was noticed in the green at very low level (1 footlambert) compared to the 39 footlamberts green hue.

TABLE II BRIGHTNESS LEVEL DATA

	Perceptible Change		Measured Chromaticities					
	YES	NO	LOW		MEDIUM		HIGH	
			x	y	x	y	x	y
Red		X	0.595	0.352	0.618	0.343	0.611	0.352
			at 1 fL		at 4 fL		at 8.5 fL	
Green	At very low level		0.243	0.704	0.234	0.720	0.235	0.720
			at 1 fL		at 20 fL		at 39 fL	
Blue		X	0.144	0.120	0.143	0.123	0.142	0.123
			at 1 fL		at 1.5 fL		at 3 fL	

1.4.2.12 <u>Color Misregistration.</u> The color misregistration was measured for the following color combinations:

Red and green superimposed
Red and blue superimposed
Blue and Green superimposed
and white (red, green, blue)

The test for registration was performed as follows. A window pattern as shown in Figure 11 was formed with one primary color for the background and another for the window. Since the red, for example, is in one field and the green is in a different field we could examine the vertical intersection between the two fields with a microscope; and determine the amount of color misregistration along this line by direct measurement on the microscope reticule. Since the window can be set to any size, we can measure the misregistration over the entire field using this method. The misregistration in parts of a spatial cycle was calculated as shown in Figure 12.

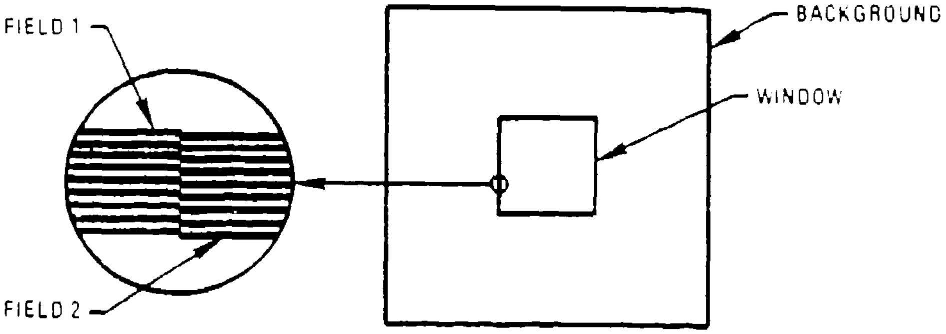


Figure 11 Window Pattern

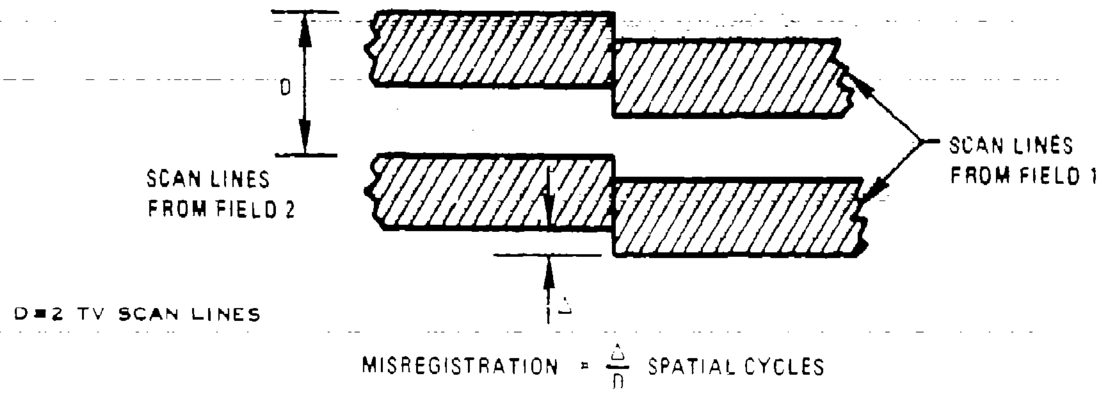


Figure 12 Definition of Color Misregistration

1.4.2.13 Flicker. The flicker performance was measured by positioning an observer on-axis with the display screen with the eye located at a nominal distance of 18 inches from the display screen. The field rate was determined by measuring the period of the vertical sync pulses with a Tektronix model 453 calibrated oscilloscope.

Peripheral or foveal flicker thresholds were then determined by increasing the display brightness from a low level until flicker was observed. This was correlated by lowering the brightness from a high level until all flicker disappeared. The brightness levels were measured with a Spectra Model UB-1505 calibrated spot photometer. Ambient light level was less than 0.1 fL.

SECTION 2

SYSTEM RECOMMENDATIONS

This section of the report will be a discussion of the requirements versus the test results obtained from the experimental display. The potential for improved performance will be covered as well as the recommendations for future development of this type of display device. Finally, some projections of present technology are made in an effort to predict the ultimate performance capabilities of the field sequential display for the applications intended by the Air Force.

2.1 DISCUSSION OF TEST RESULTS VS. REQUIREMENTS

The present experimental display represents the first cut attempt to meet the very stringent performance requirements set by the Avionics Laboratory. In the design of the experimental display, an important limitation was the financial resources available to design and implement a display which at the time of specification was at the present state-of-the-art. Philco-Ford's design philosophy was to construct with the company committed resources, the best possible implementation of the proposed display. This display to be used for the purpose of providing a test bed to test the high resolution field sequential concept against the Avionics Laboratory requirements. Every attempt was made in the specification of the components, in the design and in the implementation of the existing real-time improved color image display to produce a display which would meet the requirements set by the Air Force. The result of this program is an excellent high resolution full-color TV display which, still falls short in certain requirements. However, since a hardware implementation of the high resolution, field sequential display exists it is an excellent tool for the evaluation of this type of display. Much valuable data has been obtained from the display pertaining to the characteristics and limitations of a field sequential system and many specific ways to improve the performance of the existing hardware implementation have been identified.

Each test parameter listed in paragraph 1.4.1 is discussed below considering both the specific performance results obtained for the experimental display and the specific improvements which could bring the display performance up to or beyond the Air Force requirements.

2.1.1 Spatial Frequency Response

2.1.1.1 Comments on Test Results. The spatial frequency response of the lens-CRT combination is affected most directly by the three factors itemized below.

- lens spatial frequency response
- CRT spot size
- light trapped in the faceplate of the CRT

The measured depth of modulation for the projection lens with a square wave test pattern (USAF 1951) was 85% at 13 TV lines/mm over the entire field. Thus the lens has a good transfer function capability at the 1000 TV lines/picture height resolution.

The CRT provided by Thomas Electronics has a shrinking raster spot size of 3 mils at 15,000 footlamberts full output (using no color filters). For the 3.1 inch raster, the depth of modulation equals 76% in the center of the screen at 1000 TV lines and 44% in the corners at the same resolution.

The resulting center and corner modulation on the display screen are then calculated as 65% in the center and 32% in the corners. We realized in specifying the 5" CRT that the corner modulation would not make 50%. However, the cost and schedule for a 7-inch fla[illegible] e CRT and a larger lens versus these costs and schedules for an established design 5-inch CRT using a smaller lens dictated the less expensive alternative. During the building of the display, serious problems were encountered in the design and production of the lens for use with the 5-inch CRT. These problems would have been only compounded by the specification of a lens designed to work into a 7-inch CRT, and the display does provide 50% modulation in the center area of the CRT so that the quality of a color display with 1000 TV line resolution at 50% modulation can be studied in a meaningful way.

2.1.1.2 Recommendations. The overall modulation can be increased to 50% in only one way. The ratio of the raster size to the spot size must be increased. This can be accomplished either by obtaining a CRT with a smaller spot size or using a larger CRT and maintaining the spot size at 3 mils. If a 7-inch CRT with a 4 inch square raster were used and we could

maintain a 3-mil spot size (shrinking raster); then, from Figure 38, for a spot width-to-peak separation ratio ~ 0.375, we obtain a modulation ≈ 92% in the center and 76% in the corners at 1000 TV lines (again assuming 30% growth to the corners).

The most practical solution to providing a production display with 50% overall modulation is to utilize the 7-inch CRT with a larger lens. The cost will be higher and the weight will increase somewhat, but this solution is judged more feasible at this time than attempting to obtain a high-beam current 5-inch projection CRT with the required 2.3-mil center spot size.

2.1.2 Brightness

2.1.2.1 Comments on Test Results. For the 9,000 fL of white light available from the CRT, the calculation for the brightness yields about 33 fL which agrees very well with the measured result.

The total measured output of the CRT equals 15,000 fL and one might question why this amount of light is not available as white light. The reason is that a high ratio of green to blue phosphor was required to create a high green purity. With 15,000 fL of white, we could get 55 fL highlight brightness on the present 14" x 14" screen. Figure 13 shows the variation in screen brightness with CRT brightness where the screen size is a parameter. For a 10" x 10" screen the screen brightness is 94 fL for a 15,000 fL CRT brightness and 56 fL at 9000 fL. The 10" square screen will give the same resolution and much higher brightness than the 14" x 14" screen and could be satisfactory for many applications.

An alternative to changing either the CRT brightness or the screen size would be to use a faster lens. In such a case the lens must be changed to provide optical speeds in the range of f 0.8 to f 0.83 as shown in paragraph 4.1.2. With the combination of the 15,000 fL white phosphor and the f 0.80 lens the highlight brightness would be increased to 78 foot-lamberts on the 14" by 14" screen. Diffraction Optics of Mountain View, California, has bid on the construction of an f 0.8 lens suitable for use in the real-time color display.

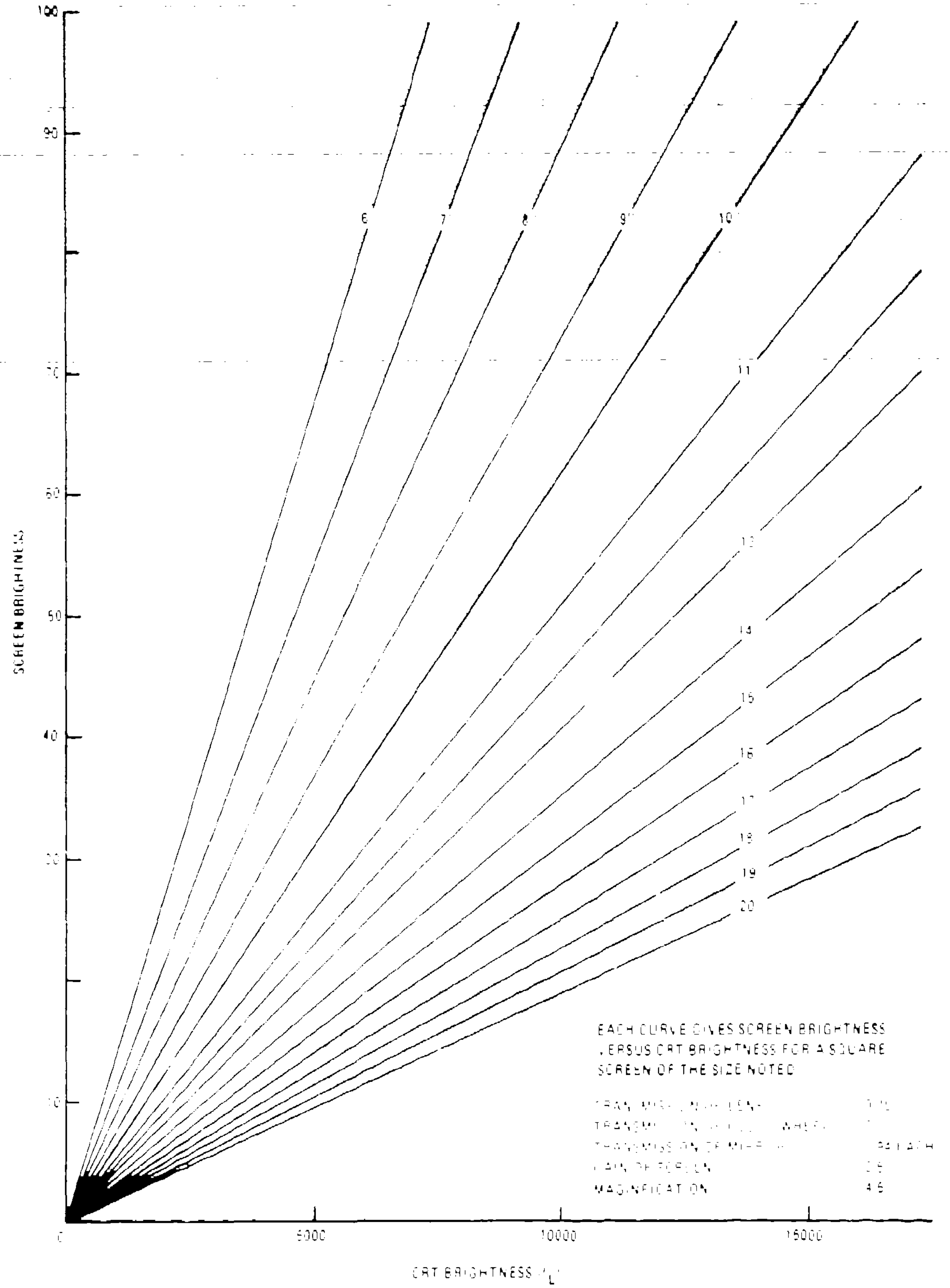


Figure 13 Variation in Screen Brightness vs Screen Size

2.1.3 Shading

2.1.3.1 Comments on Test Results. The 50% falloff to the corners of the raster is caused by falloff in the projection lens and the 2.5 gain projection screen. Shading correction was not implemented on the experimental display since no additional data would be gained for the additional incurred cost. Additionally, due to the approximately logorithmic response of the eye to luminance changes, a gradual falloff in brightness of up to 50% from the center to the edge of the screen is not objectionable to an observer.

2.1.3.2 Recommendations. Shading correction to ±5% over the screen can be implemented in a future prototype display fairly readily. A clear disadvantage of providing this type of shading correction would be that the center highlight brightness would be reduced by 50% in order to obtain the ±5% uniformly. For all tests except possibly hue vs color brightness this degree of uniformity is not needed to attain an apparently uniform brightness to an observer.

2.1.4 Gray Scale

Eleven each $\sqrt{2}$ gray shades are provided by the display where the reference brightness is taken as 1 fL. This figure is limited only by the peak brightness of the display. To obtain 12 each $\sqrt{2}$ gray shades, it will be necessary to increase the highlight brightness of the display to 44 fL

2.1.5 Black and White Contrast Ratio

2.1.5.1 Comments on Test Results. Figure 14* shows the contrast ratio of a CRT as a function of the attenuation in the faceplate where this attenuation is due to the use of a neutral absorbing glass such as Filterglass. It is important that the attenuation be provided uniformly throughout the thickness of the glass faceplate rather than as an attenuating layer on the surface of the CRT faceplate. Since the optical contact is about 20% for settled phosphor of the type used in the display, the graph shows that an attenuation of 23% is sufficient to yield a 75:1 detail contrast ratio.

* Zworykin & Morton, Television, p. 418, 1954.

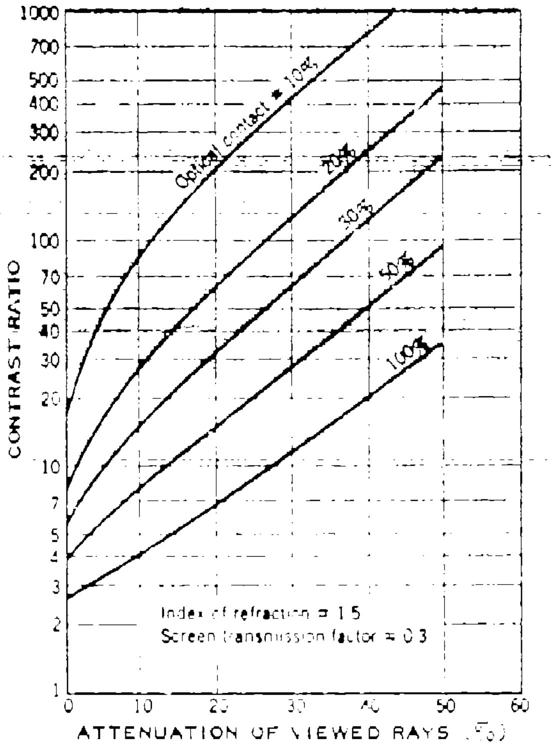
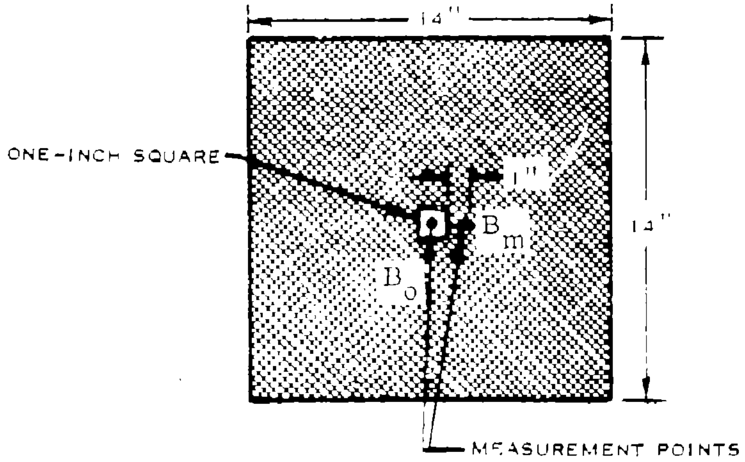


Figure 14   Contrast Ratio as a Function of Attenuation in the Faceplate

The large area contrast even at the lower brightness levels achieved in the experimental display was 50:1 for the conditions shown in Figure 15.

For display presentations which activate less than 15% of the raster area the total amount of scattered light levels in the CRT is much lower and, even with a clear faceplate, the contrast ratio will approach the large area values.



$$C_r = \frac{B_o}{B_m}$$

Figure 15   Large Area Contrast Ratio

The attenuating faceplate was not requested for the experimental tube because of anticipated difficulty of obtaining within schedule a high brightness projection CRT with this type of faceplate. The vendor selected did not normally stock or produce such projection CRTs. For these reasons a Thomas Electronics (Wayne, N.J.) Type 5M117 (5" flatfaced clear projection CRT - see page 82) was utilized since all of the proper mounting assemblies and deflection components were available from Philco-Ford vendor stock. EMI Electronics Limited in Britain is currently manufacturing a low-power film scanning Type MX69 CRT with a neutral tinted faceplate. Investigation is being carried out to determine the suitability of the faceplate material for projection CRT use.

2.1.5.2 Recommendations. For conditions where less than 10% of the screen is energized by the electron beam, the clear face CRT yields useable displays at a contrast of approximately 10:1 although halation is apparent at low ambients.

If very high (75:1) detail contrast is to be obtained for high-duty cycle patterns, then at least 23% attenuation should be provided in the faceplate. Another approach which has been taken to reduce halation and improve the detail contrast ratio is to provide a very thin subscreen located behind the CRT faceplate. This method is very effective at reducing halation, but has not been used much in projection CRTs because of the present inability of this thin subscreen to dissipate the high screen power of a projection CRT. Also, CRTs have been manufactured in which a thin black particulate layer was deposited on the inner surface of the CRT before the phosphor coating is deposited. Large improvements in detail contrast were reported when using this method.

The last method for improving the detail contrast is to use a fiber optic faceplate CRT. Again, the results are excellent, but the fibers attenuate the light output of the CRT, and the faceplate is more subject to dielectric breakdown and thermally induced cracking than a single piece faceplate.

More detailed analysis and tradeoff study of the various alternatives on the system level will be required to determine the optimum solution for obtaining high detail contrast ratios.

2.1.6 Color Gamut

2.1.6.1 Comments on Test Results. The subjective effects of the present primaries are dependent on the available comparison color fields. The red primary of the experimental display, for example, appears as a definite red-orange when compared to a deep red with dominant hue of 630 nm or greater. In the absence of a comparison color field, the red appears saturated and clearly elicits a red identification rather than orange.

A similar situation holds for the green primary which in comparison with a 530 nm primary appears yellowish-green. Again in the absence of comparison color fields, the green is evidently saturated and appears as a light green without any particular yellow characteristics. The blue primary is very good (dominant hue of 476 nm) and appears very blue and saturated in comparison with a blue color field. The dominant hues of the red and green primaries are almost entirely dependent on the phosphor spectra and not the color wheel filters. The red and green phosphors would need to be changed to different types if different dominant wavelengths are desired. The blue primary is developed by filtering a broad band spectrum and can be changed by varying the filter band edges.

2.1.6.2 Recommendations. At this time, better phosphors for use in the projection CRT have not been found. The alternative of using broad band phosphors rather than narrow band is not good since it is difficult to obtain high primary purities when using filters to select a portion of a broad band spectrum. If the filters can be made narrow band enough to yield a high-purity primary, then most of the light output of the phosphor is wasted.

In summary, the present phosphors are the best in terms of high performance in projection applications. The dominant hues could be improved somewhat, but new phosphors will be required to permit this change.

2.1.7 Purity

2.1.7.1 Comments on the Test Results. Both the red and the green purities were within $\pm$ 5% of the requirement of 90%. As discussed in Section 3, the purity of the blue is very

dependent on the blue filter bandwidth because of the broad spectrum blue phosphor used. If the blue filter bandwidth were narrowed a 90% blue could be obtained, but the maximum luminance of the blue would be even less than that of the present 80% purity of the experimental display. It is generally true, that the maximum luminance of a primary must steadily decrease as the purity of that primary is increased toward 100%. The reason for this decrease is almost obvious since a 100% pure color contains only one wavelength of light and thus includes very little energy. For this same reason, the narrow band rare-earth phosphors used in the experimental CRT gave the optimum results by concentrating almost all their light output into a very narrow spectral spike (for example, see Section 3, Figure 28).

2.1.7.2 Recommendations. To increase the blue purity to 90%, a narrower band color filter must be selected. The brightness of the hue primary will decrease when this is done. The green purity is acceptable at 89%. The purity of the red primary can be increased optimally by finding a better phosphor. The present red (see Figure 29) has lower purity because of the multiple peaks at wavelengths shorter than 620 nm. These peaks are close enough together that they cannot be easily separated with the red filter without seriously attenuating the luminance of the red primary.

2.1.8 Color Brightness

2.1.8.1 Comments on Test Results. The present white highlight brightness is 33 footlamberts. This must be increased by 227% in order to obtain 75 footlamberts. The present color brightness and the 227% values are:

	B (fL)	227% B (fL)
Red	8.2	18.6
Green	46.0	104.0
Blue	3.8	8.6

The present blue primary brightness would be below the required 15 fL even for the increased brightness from 33 fL to 75 fL. Two possible solutions to the problem are:

1. Decrease the purity of the blue primary by increasing the blue filter bandwidth.

2. Find a rare-earth blue phosphor with a narrow-band output so the ratio of blue to green can be increased. (See Section 3 for discussion.)

2.1.8.2 Recommendations. The overall highlight brightness will need to be increased to bring up the color brightnesses. An investigation should be carried out with a CRT manufacturer in conjunction with a phosphor manufacturer such as U. S. Radium to find a better narrow-band rare earth phosphor. This appears to be the only practical alternative if high blue purity is required.

2.1.9 Color Brightness Shades

The color brightness shades are calculated mathematically from the highlight brightnesses of each primary. 15 fL in each primary is sufficient to yield 8 each $\sqrt{2}$ shades in each primary with a 1 fL reference.

2.1.10 Color Linearity

2.1.10.1 Comments on Test Results. The perceived linearity of the red and blue primaries showed no change as the brightness was varied from minimum to maximum levels.

At very low brightness levels (1-2 fL) a small hue shift toward lower purity was perceived in the green primary. This shift is verified by the chromaticity measurements shown in Table I (paragraph 1.4.2.11). There is no certain explanation for this shift, but it may be due to slight super or sublinearity effects in the phosphors (see paragraph 3.2.2, Figure 17).

2.1.10.2 Recommendations. The phosphors are judged acceptable in the experimental design from the standpoint of color linearity. The green shift occurs at 1-2 fL levels and is barely perceptible.

2.1.11 Color Misregistration

The measured misregistration was less than 1/8 spatial cycle at 1000 TV lines resolution. This performance is typical of field sequential displays provided proper shielding of the electron gun is made to prevent stray electromagnetic fields from disturbing the picture, and the deflection circuits and high-voltage power supply are free from noise which could instantaneously change the picture size.

2.1.12 Flicker

2.1.12.1 Comments on Test Results. No flicker is perceptible in the foveal vision of 33 fL and a field rate of 172 Hz. Where the entire 14" x 14" field is illuminated and the observer is fixated near the center of the screen, a very slight amount of peripheral flicker is perceived.

2.1.12.2 Recommendations. The field rate will be raised to 180 Hz which will improve the peripheral flicker performance. The peripheral flicker presently is not objectionable. Also, as can be seen from Figure 18, the critical fusion frequency only changes from 41 Hz to 43 Hz when the light output is raised from 33 fL to 75 fL. No degradation in flicker performance is predicted by this change in brightness.

2.1.13 Input Power

The input power is 450 watts of which an estimated 60 watts is used by the test pattern generator which would not normally be included in the display.

2.1.14 Size

The size is dictated primarily by the optical components and the screen size, although most of the volume is used in the present configuration. Different optical configurations can be studied to determine whether the package size can be reduced.

2.1.15 Weight

The experimental display weighs 311 pounds. 10 pounds can be removed when the test pattern generator is taken out of the display along with its power supply. The present mounting plate and optical assembly use a much heavier plate than needed. This structure can probably be lightened by twenty pounds.

It appears practical to reduce the display weight to 210 pounds. Section 5.3 outlines procedures that need to be taken to accomplish this.

2.2 RECOMMENDATIONS

To ensure the optimum performance for the projection display application the following must be considered on the next implementation of a sequential color display.

To improve resolution, a 7-inch flat face CRT should be used which would allow for larger CRT image. A lens redesign would be required to allow for reduced magnification and larger front and rear lens elements. 1000 lines resolution at 50% modulation will be available over the entire field.

Brightness can be increased several ways. An f 0.8 design is practical which would be an improvement over the present f 1.0. The purity of the green can be sacrificed to yield a brighter balanced white at the CRT. Increasing the accelerating voltage would increase the light output. The latter two changes could increase the CRT output to 12,000 ft lamberts. Reducing the magnification due to using a larger CRT image will also increase the brightness. Using the formula and data presented in Section 4.1.2, where screen brightness =

$$B_s = \frac{BT_L \; T_F \; T_M^2 \; G}{4(M+1)^2 \; f^2 + M^2}$$

and letting $f = 0.8$

$M = 3.5$

$$\text{yields } B_s = \frac{12{,}000\,(0.75)\,(0.31)\,(0.94)^2 2.5}{4(4.5)^2\,(0.8)^2 + (3.5)^2} = 96 \text{ fL}$$

Using a smaller screen such as 10 inch by 10 inch (considered suitable for command and control applications), would result in 188 fL output brightness.

As is indicated above, sacrificing green purity would give higher light output. Increasing the blue purity should be considered concurrently. An investigation should take place with the goal of developing a phosphor of high blue purity.

Black and white detail contrast ratio can be improved to 75:1 by utilizing a 23% attenuating type glass for the CRT faceplate. For the 14" x 14" screen display the output brightness is then approximately 74 footlamberts. The output on the 10" x 10" display would be approximately 145 fL.

Shading correction to a ±5% uniformity is not recommended if the display is used only for a human observer since a gradual 50% falloff is not objectionable to most observers. Correction to only a ±30% variation will give excellent visual results and would cut the output luminance to 52 fL for the 14" x 14" screen, and to 101 fL for the 10" x 10" screen.

Volume and weight are subject to each individual packaging requirement and can be adjusted accordingly.

SECTION 3

CRT AND COLOR WHEEL FILTER SELECTION

3.1 BACKGROUND

One area of significant development occured in the selection of the CRT phosphors and the color wheel filters. New phosphors were needed to satisfy the requirements for the CRT since the existing registered phosphors were deficient in one or more of their characteristics relating to chromaticity, linearity, and brightness. To permit specification of the red, green and blue phosphors and their ratios, a series of computer programs were developed to permit rapid evaluation of the CIE coordinates for arbitrary phosphor and filter combinations. These programs also permit the designer to iteratively find an optimum combination of phosphors and filters to meet certain purity specifications of the primary colors, while still obtaining the maximum possible light output.

In order to best understand the process used in the phophor and filter selection, the system constraints on the phosphor and filter relation are listed and discussed in Section 3.2. Section 3.3 is concerned with the design procedures followed in selecting and specifying the color wheel filters. Areas for further study and development are then summarized and discussed in Section 3.4.

3.2 SYSTEM CONSTRAINTS

The system constraints pertinent to the selection of the phosphors and the filters are:

- Chromaticity of color primaries (purity and hue)
- Color linearity
- Brightness
- Flicker and phosphor persistence

The detail requirements are outlined below.

3.2.1 Chromaticity of Primaries

The required chromaticities for the primaries are specified in two paragraphs of the Wright Patterson Air Force RFP F33615-70-C-1417.

"4.2.1.11 Color Gamut: All colors within the triangle on the CIE chromaticity diagram whose apexes are approximated by the hues of 630 nanometers, 580 nanometers, and 470 nanometers (See Figure 1)."

"4.2.1.14 Purity: Purity will be at least 90 percent in all primary hues."

These color gamut and purity specifications are converted to chromaticity specifications in Section 3.3 where Illuminant "C" is used as the standard in calculating the purities per paragraph 4.3.7 of the RFQ quoted below.

"4.3.7 CIE Colors: The following wavelengths will be defined as standards for their respective colors."

Red	-	700.0 nm (nanometers)
Green	-	546.1 nm
Blue	-	435.8 nm
White	-	Illuminant C

3.2.2 Color Linearity

"4.2.1.13 Color Linearity: There will be no significant or perceptible change in hue with a change in brightness."

Kuehn and Luxenberg (Display Systems Engineering, McGraw-Hill, 1968), discuss the effect of luminance levels on apparent hue perception. Figure 16 below illustrates the Bezold-Bruke phenomenon.

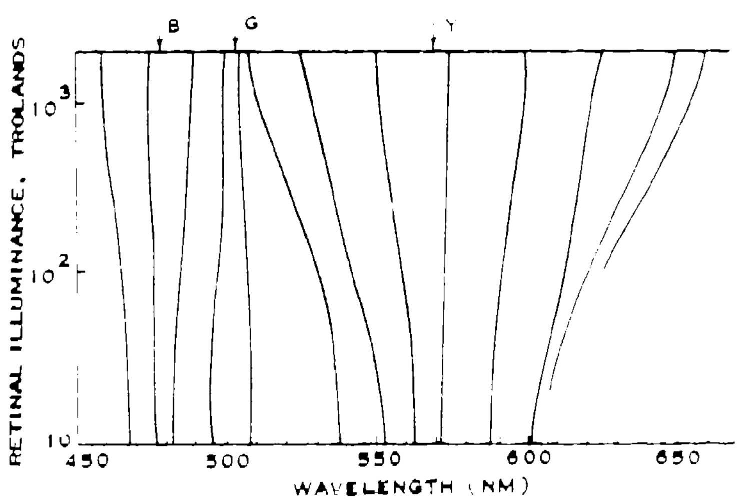


Figure 16 Illustration of the Bezold-Bruke Phenomenon

A shift equivalent to as much as 10 to 20 nanometers in dominant wavelengths is apparent at some wavelengths. Since the retinal illumination in the various hues varies from near zero to over 100 trolands, color shifts may be experienced. The significance or perceptibility of these shifts is dependent on the observers and the extent of change in retinal illumination. This is a fundamental property of the human eye difficult to compensate in any display. It is evident that color linearity shifts due to the Bezold-Brucke Phenomenon, if perceptible, cannot be compensated for by any choice of phosphor or color filters. The test results (Section 12) show that some perceptible color shift occurs for the green primary even though the measured chromaticity has not changed appreciably. Color linearity can also be significantly affected by super or sublinearity effects in the phosphors. These two effects are shown in Figure 17.

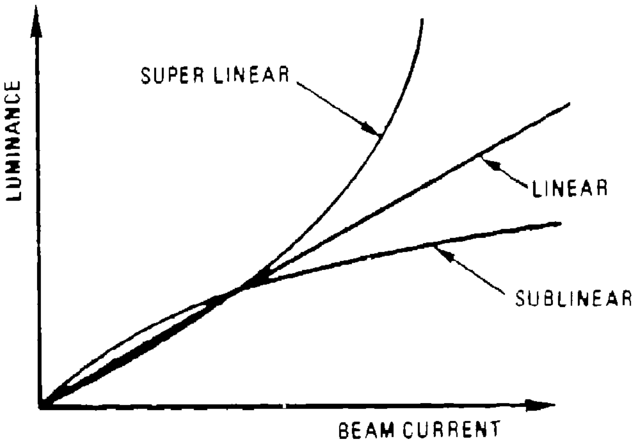


Figure 17 Super Linear and Sublinear Effects in Phosphors

A combination of a linear phosphor and either a sublinear or super linear phosphor will definitely change color with variations in beam current.

3.2.3 Brightness

"4.2.1.5 Brightness: The maximum brightness of a balanced white output shall be at least 75 footlamberts."

"4.2.1.15 Color Brightness: At least 15 footlamberts in each primary hue."

The brightness requirement of paragraph 4.2.1.15 of the RFQ must be interpreted in terms of the brightness (or luminance) of the CRT. Subsidiary to this the color brightnesses can be determined once the chromaticity of the primaries is known.

The CRT brightness can be calculated by means of the following formula.

$$B_S = \frac{B\, T_L\, T_F\, T_M^{\,2}\, G}{4(M+1)^2 f^2 + M^2}$$

where:

B_S = Screen brightness in footlamberts
B = Brightness of CRT in footlamberts
T_L = Transmission of glasses in lens = 0.75
T_F = Transmission of color wheel for "Illuminant C" = 0.31
T_M = Transmission of optical folding mirror = 0.94
G = Gain of rear-projection screen = 2.5
M = Magnification (14" from 3.1") = 4.5
f = f-stop of projection lens = 1.0

For a specified screen brightness, the required CRT brightness is found by rearranging the above formula. We obtain:

$$B = \frac{B_S(4(m+1)^2 f^2 + m^2)}{T_L\, T_F\, T_M^{\,2}\, G} = 275\, B_S$$

for the above design parameters
for a 75 footlambert screen brightness

$$B = \frac{75[4(4.5+1)^2\, 1^2 + (4.5)^2]}{(0.75)\,(0.31)\,(0.94)^2\, 2.5}$$

$$B \cong 20{,}627 \text{ footlamberts}$$

Thus, the specifications require a CRT brightness of 20,627 footlamberts in white to achieve 75 footlamberts screen brightness on a G=2.5 projection screen with the specified 14" by 14" screen size, and the chosen optics.

The color brightnesses were estimated by assuming that the red, green, and blue components are so chosen that the full amounts of each are used to produce white. The relative luminances of "typical primaries" when matching Illuminant C for field-sequential (low flicker) primaries are:*

Red	0.309
Green	0.474
Blue	0.217
Total:	1.000

From the above we see that the amounts of red, green, and blue required to match footlamberts of field sequential Illuminant C are:

Red = 0.309 x 75 = 23 footlamberts
Green = 0.474 x 75 = 36 footlamberts
Blue = 0.217 x 75 = 16 footlamberts

These calculations for the resulting color brightnesses are approximate because the relative amounts of the primaries required to match Illuminant "C" are dependent on the chromaticity of those primaries.

3.2.4 Flicker and Phosphor Persistence

"4.2.1.6 Flicker: The display shall be flickerless when operated at a brightness of 75 footlamberts."

The dependence of flicker on retinal illumination is shown in Figure 18. Retinal illumination is measured in trolands where a troland is defined as the light falling on the observer's retina from a surface having a luminance of one candela per square meter when the eye pupillary area is one square millimeter.

*See D. Fink, "Television Engineering Handbook," p. 1-31

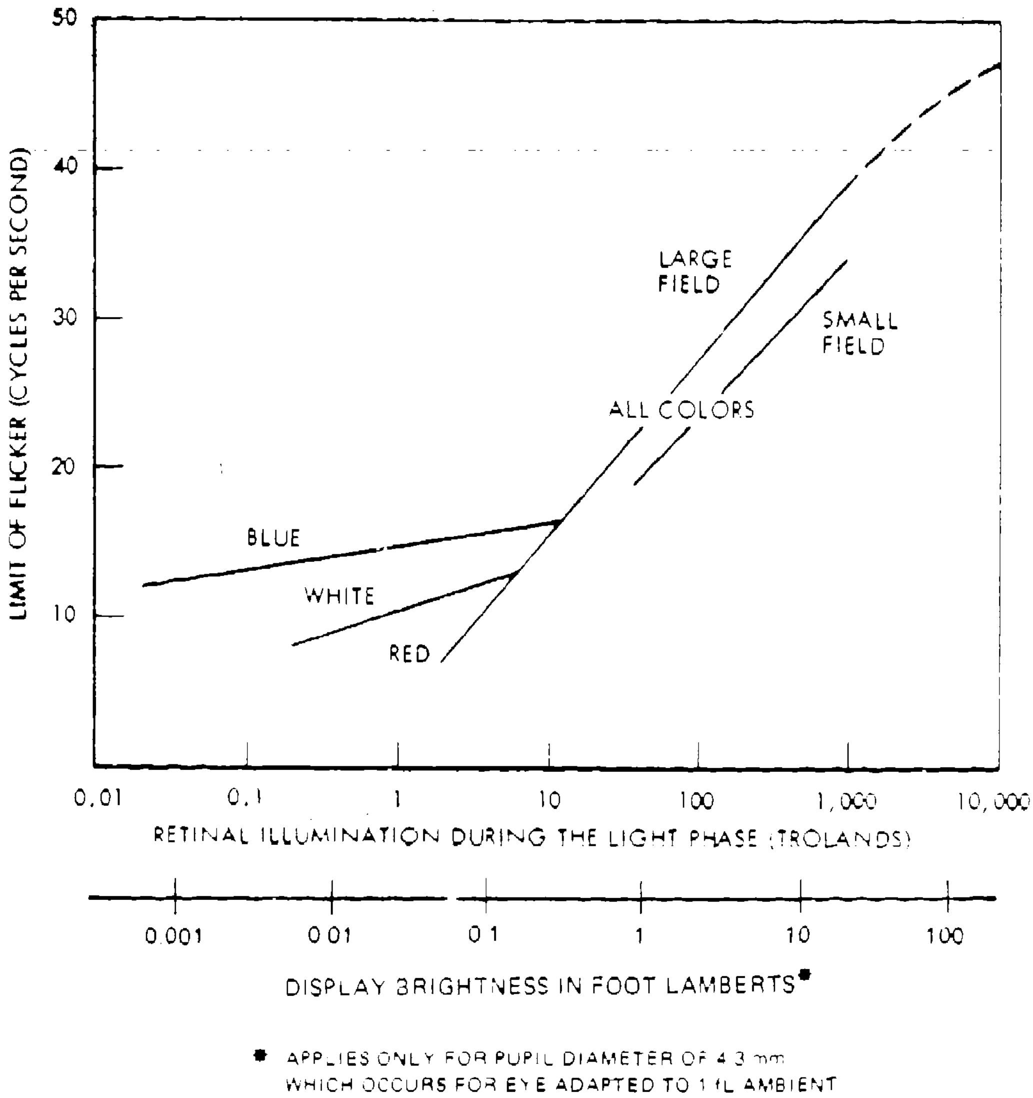


Figure 18 Dependence of Flicker on Retinal Illumination

The specifications do not specify the ambient light levels to be expected. This fact influences computation of the flicker effects because of the wide variation in pupillary areas with variation of the field luminance to which the eye is accommodated (See Figure 19). However, we can assume a worst-case low level ambient of 1 footlambert. This would yield a pupil diameter of 4.3 mm, and a corresponding pupillary area of 14.55 square millimeters.

The retinal illumination (I) in trolands is related to surface brightness (B) in candelas/sq. meter and the pupillary area (A) by the following equation:

$$I = SBA$$

where:

S = a factor dependent on A, which compensates for the decreasing efficiency of the eye with increasing pupillary area (Stiles-Crawford Effect)

For a pupil diameter of 4.3 mm, the relative brightness is approximately 80% of that which would be expected if the apparent brightness of a diameter of 2 mm was multiplied by the increased area of a 4.3 mm diameter pupil. Thus:

$$I = (0.8)(B)(14.55)$$

and for a screen brightness of 75 footlamberts

$$I = (0.8)(75)(14.55)(3.426) = 2991 \text{ trolands}$$

which yields a critical fusion frequency of approximately 43 cycles per second.

Since the minimum color field frequency is 50 Hz, we did not expect flicker at the 75 foot-lambert level for information appearing in both color fields.

The phosphor persistence should be such that the light output from the CRT decays to less than 10% of maximum in one field period. This condition is necessary because the color fields occur in the sequence red, green, blue, etc. If the light due to phosphor excitation during the preceding field has not decayed to a sufficiently low level when the next field begins, then the purity of all the colors will be incorrect. Also, if the persistence is longer than one field,

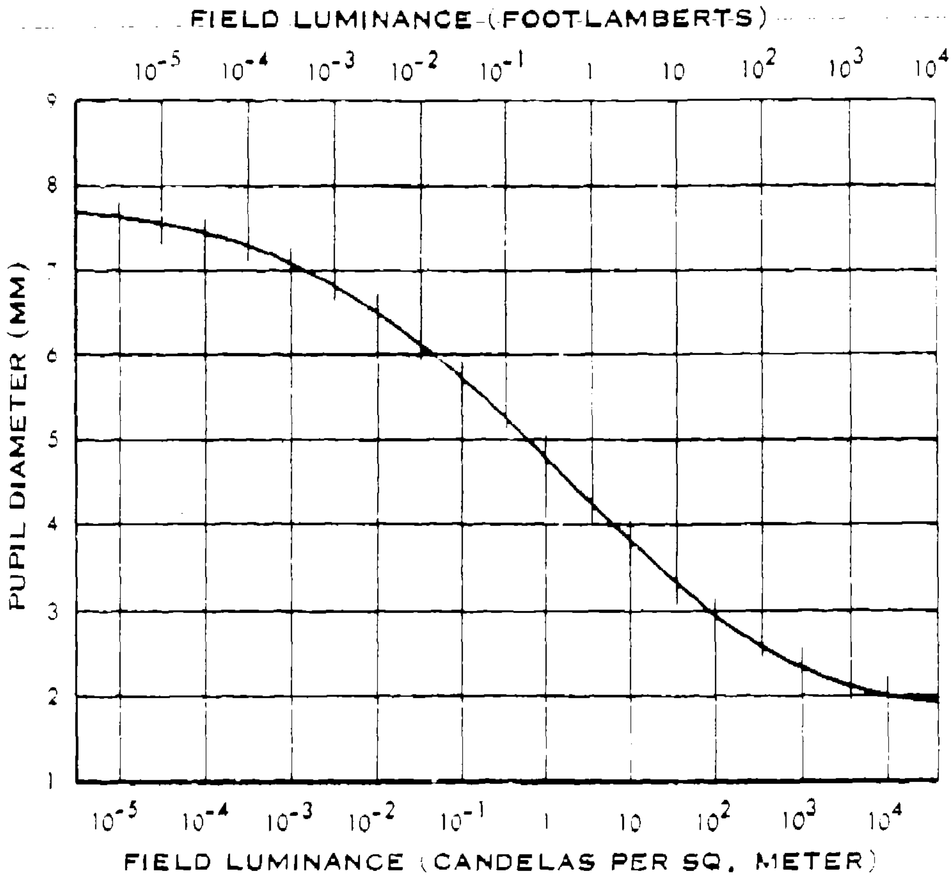


Figure 19 . ize of Pupil Diameter

smearing may occur when the data is changing rapidly. From the flicker considerations above, a decision was made to operate the display with a color field rate of 50 to 60 Hz. Since there is one red, one green and one blue field composing each color field, the individual field rates are 150 Hz and 180 Hz for the 50 Hz and 60 Hz color field rates respectively. The phosphor, therefore, must then decay to 10% or less in 1/180 sec = 5.55 milliseconds as compared to $\frac{1\text{sec}}{150}$ = 6.65 milliseconds in the 150 Hz case. On the other hand, the persistence of the phosphor should not be too short or the brightness requirements are not achieved. This is illustrated in Figure 20.

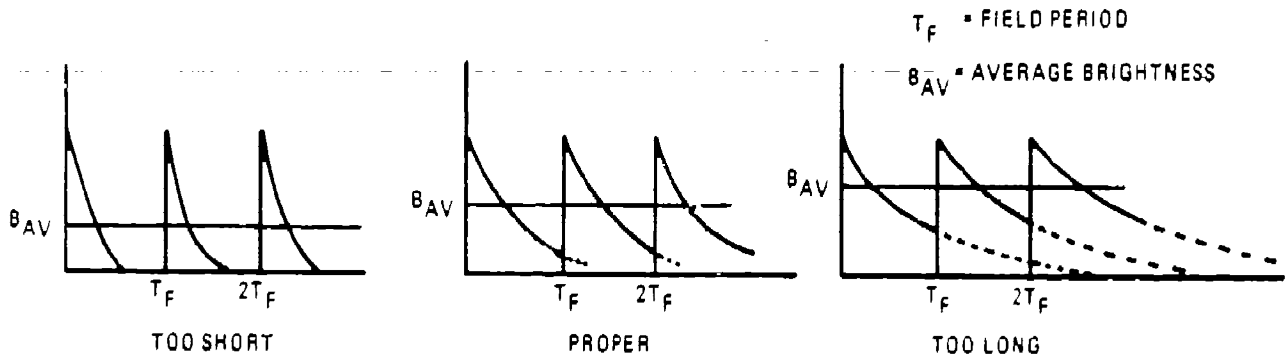


Figure 20 Persistence of Phosphors

3.2.5 <u>Summary of System Constraints</u>

- Chromaticity of Color Primaries:
  Red: Hue-630 nanometers, purity - 90%
  Grn: Hue-530 nanometers, purity - 90%
  Blu: Hue-470 nanometers, purity - 90%

- Color Linearity
  Phosphors should be chosen with a linear response.

- Brightness
  CRT brightness = 20,627 footlambers for a 75 footlambert on-screen brightness.

- **Flicker**

  A 150 to 180 Hz refresh rate is required to eliminate flicker for all brightness levels.

- **Persistence**

  5.55 to 6.65 milliseconds maximum to the 10% level. For efficient light output, the persistence should not be too short compared to the field period of 5.55 to 6.65 milliseconds.

3.3 DESIGN OF CRT-COLOR WHEEL FILTER COMBINATIONS

From the beginning of the design for the Real Time Improved Image Color Display, the selection of the CRT phosphors and the color wheel filters were identified as areas requiring significant effort. Most of the registered EIA phosphors either had too long or too short a persistence or were not suitable for projection tube use because of non-linearity effects, short lifetime, or burn susceptability. Therefore, it was necessary to carry out testing and development effort to find phosphors which might be suitable for the application and to test these in a projection CRT.

The approach taken by Philco-Ford in solving this problem was the following. First, the general characteristics of the projection CRT were determined both electrically and colorimetrically. Then a specification (see Section 4.3) was developed and submitted to CRT manufacturers to obtain feedback on the feasibility of the projection CRT and to obtain an estimate of the cost for this development effort. Of the three manufacturers replying to our request for bid, Thomas Electronics of Wayne, N.J., was finally selected to perform the investigation of suitable phosphors and to produce one prototype color projection CRT. Thomas Electronics was chosen not only for reasons of cost, but also because they had established a close working relationship with a U.S. phosphor manufacturer who had recently developed some new, very narrow band, rare-earth phosphors. Preliminary data on these phosphors showed that they might be exactly what we were searching for. Subsequently, Thomas was allowed to begin work on the projection CRT project. The narrow band phosphors were important because of the need to separate the various color components of the phosphors with the color wheel filters to produce high purity red, green and blue primaries.

3.3.1 Available Phosphors

One of the prime requirements for the phosphors was that they should be narrow band rather than broadband. The reason for this requirement is illustrated in Figure 21. Phosphor A has a very broad spectral band with essentially equal energy at all wavelengths. The filters,

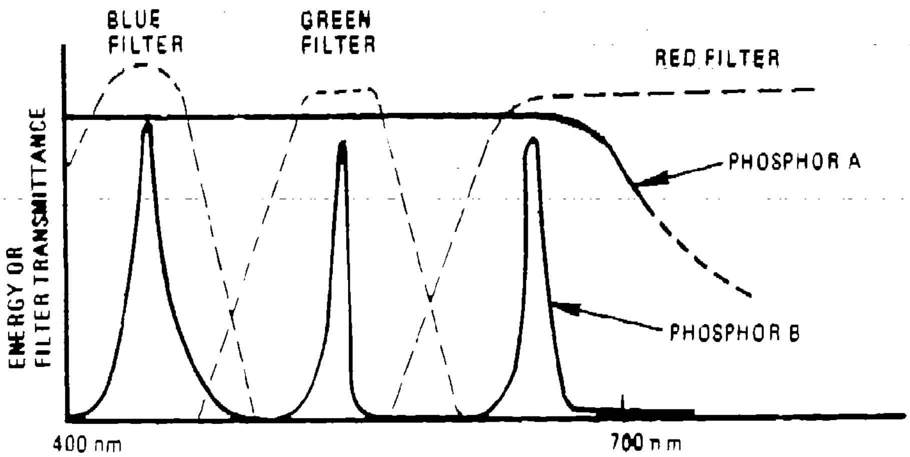
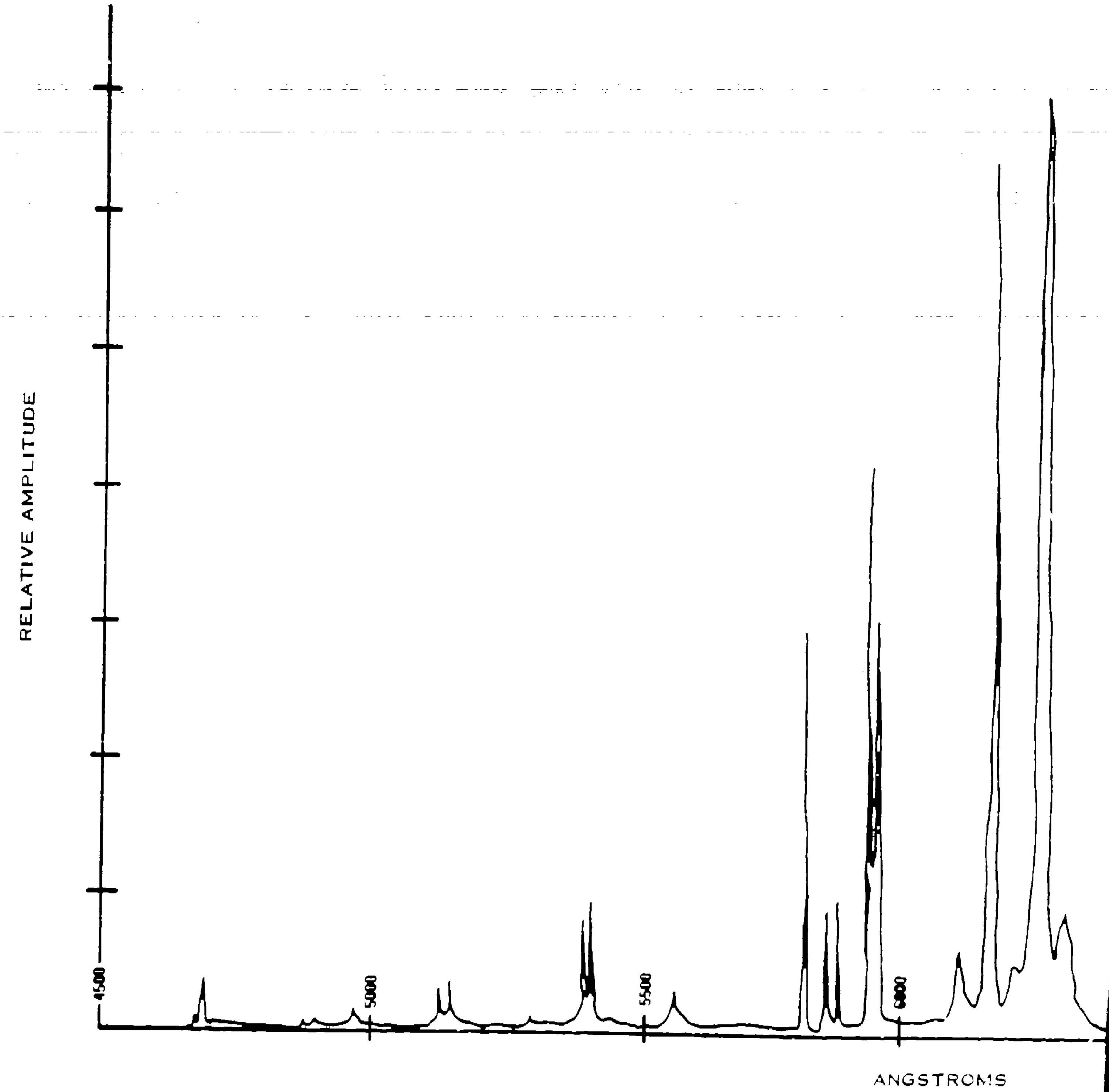


Figure 21 Broad and Narrow Spectral Bands for Phosphors

even for fairly narrow passbands, transmit such a broad band of wavelengths that the purity of the color filtered out of such a broad band spectrum is very poor, usually no better than 60%. If the filter passband is made very narrow, then usually, there is unwanted transmission at other wavelengths out of the desired passband and again the purity is poor.

The solution then, to obtaining high purity primaries, was to combine narrow band filters with spike response phosphors such as the hypothetical phosphor B, shown in Figure 21.

Thomas Electronics working in conjunction with U.S. Radium, selected a red and a green phosphor from the rare-earth phosphors which they judged were good candidates for the color projection CRT. Tests in a demountable CRT showed that both phosphors were linear with a high degree of burn resistance. The red phosphor was a common europium doped Yttrium oxy-sulfide (Y_2O_2S-Eu) with short persistence. The spectrum is shown in Figure 22. The green phosphor was a new rare-earth phosphor with Terbium doping. The peak emission for the phosphor was at 545 nm instead of the 530 nm requested in the specification, but it was


RELATIVE AMPLITUDE
4500
5000
5500
6000
ANGSTROMS

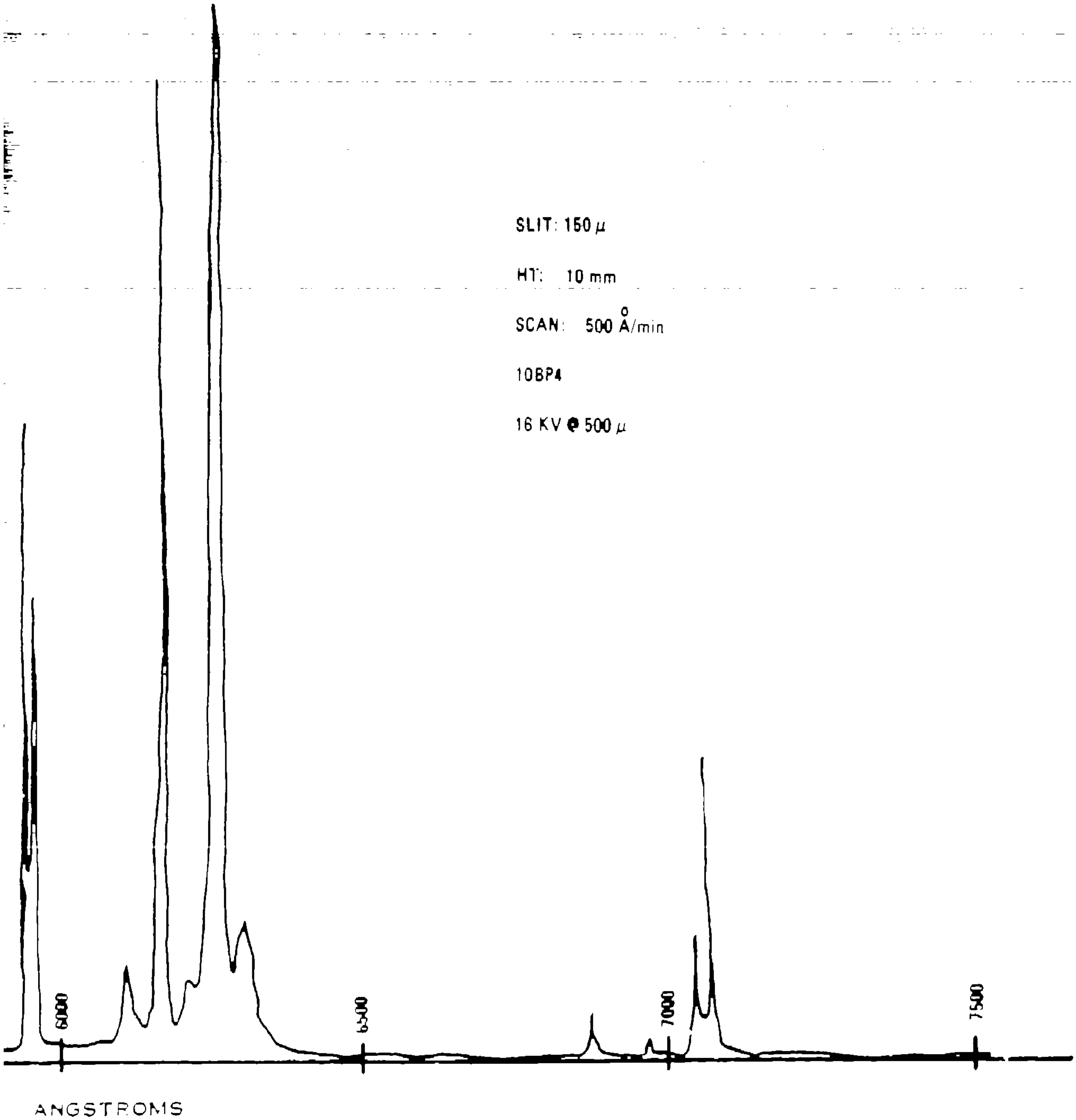


Figure 22 Red Phosphor Spectrum

the only green phosphor then available with a narrow band output. The spectrum of the green phosphor appears in Figure 23. We were now left with the problem of finding a suitable blue phosphor. U.S. Radium and Thomas Electronics tried many different phosphors, but all the narrow-band phosphors proved to be too inefficient or were non-linear under the intense current loading required for the color projection CRT. Finally, because no suitable narrow band phosphors could be obtained for the blue, a rather wide band blue was compromised on. The selected phosphor was the silicate blue used as the blue component in the common silicate version of P4. The spectrum is shown in Figure 24.

With the spectrum data on the best phosphors available and the assurance that the persistence and linearity characteristics were acceptable, Philco-Ford proceeded to develop a procedure for calculating the positions of the band edges on the color wheel filters and for determining the proper ratios of the three phosphor components required to yield 90% purities of the primary hues when viewed through the color wheel.

3.3.2 Calculation of CIE Chromaticity Coordinates

This paragraph describes the method used to calculate the CIE chromaticity coordinates of a primary given the spectrum of the phosphor used and the transmittance curve of the filter. Paragraph 3.3.3 describes the iterative procedure used to optimize the phosphor ratios and the color filter band edges to get maximum white output while maintaining 90% purity in all three primaries.

3.3.2.1 Background Theory. The CIE chromaticity coordinates are a pair of numbers (x,y) which are used to specify the hue of a given color in a quantitative manner. The (x,y) coordinates locate points on a color triangle known as the CIE chromaticity diagram. This diagram is shown in Figure 25.

The chromaticity coordinates are defined to be:

$$x = \frac{X}{X + Y + Z} \qquad \text{and note } x + y + z = 1$$

$$y = \frac{Y}{X + Y + Z} \qquad \text{thus } z \text{ is usually taken to be redundant}$$

$$z = \frac{Z}{X + Y + Z}$$

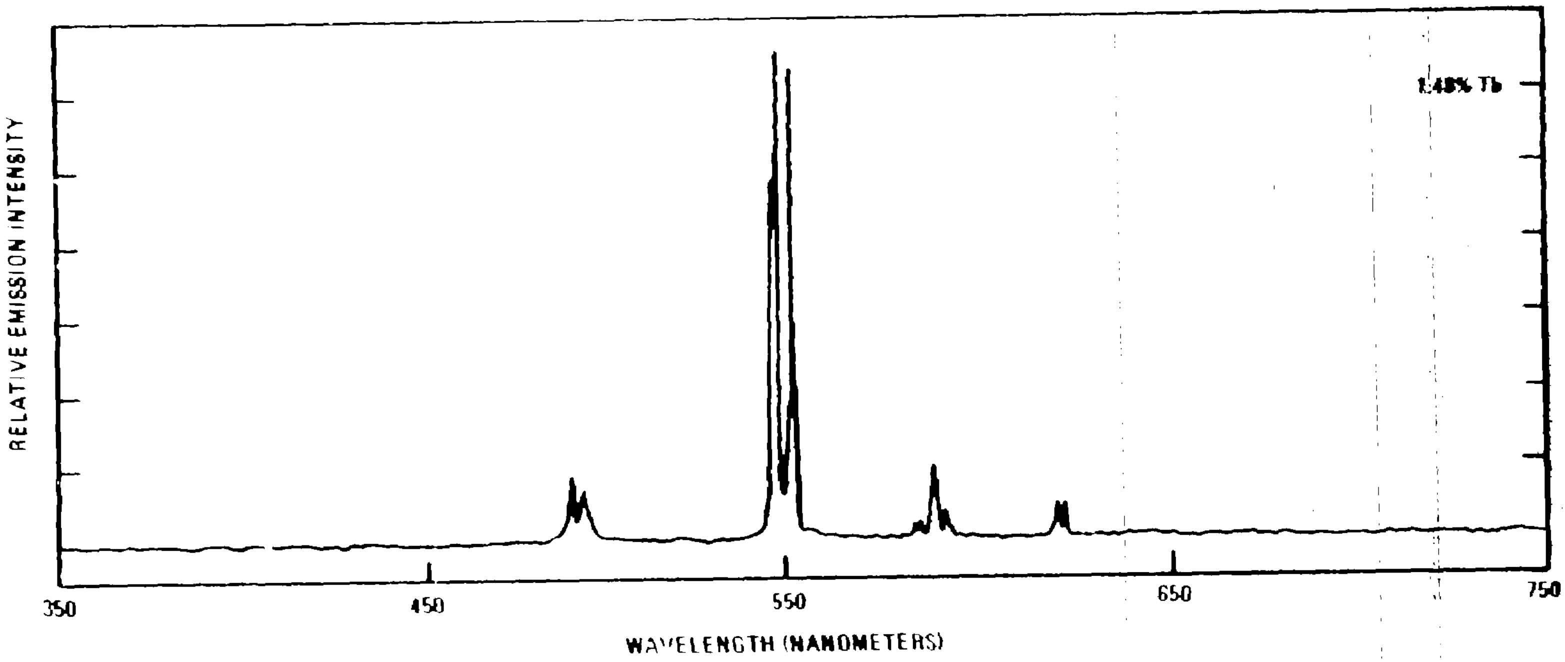


Figure 23 Green Phosphor

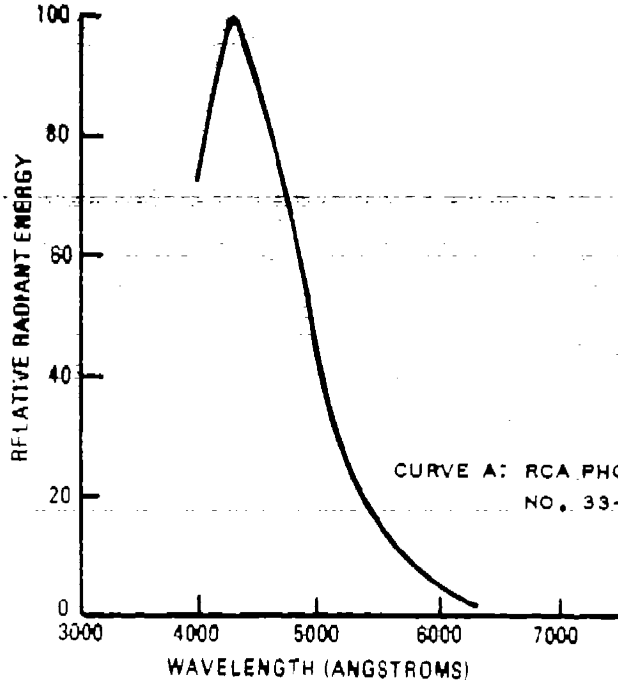


Figure 24 Blue Phosphor (Blue Component of P4-Silicate)

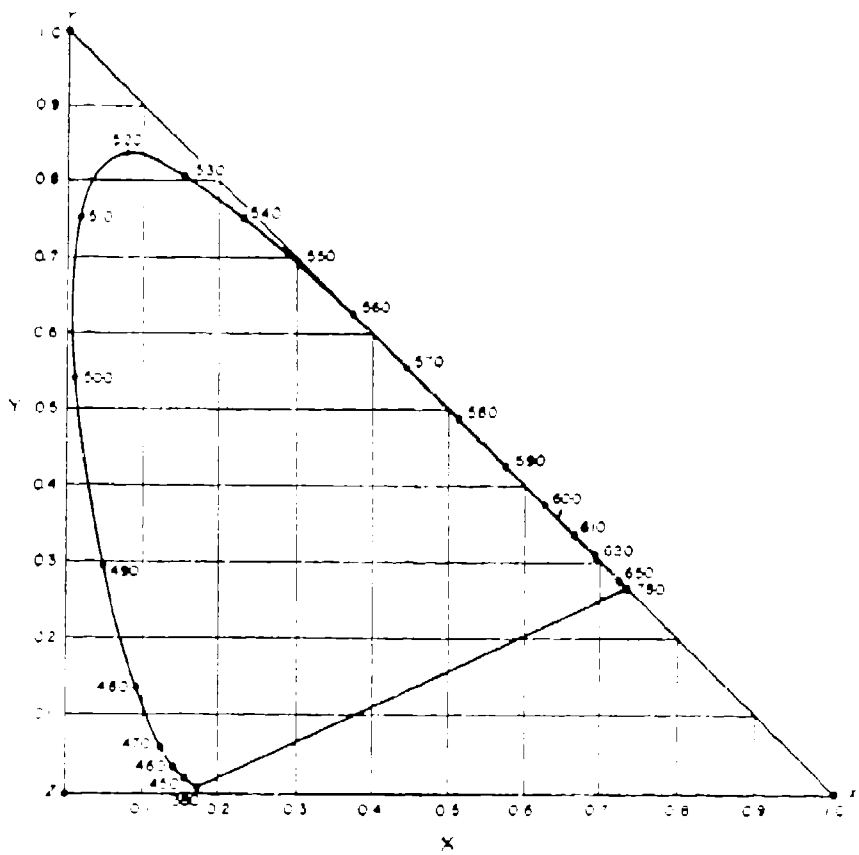


Figure 25 CIE Chromaticity Diagram, Showing Spectrum Locus and Wavelengths in Millimicrons

Where X, Y, and Z are called the tristimulas values of a given color. They represent the amounts of imaginary or non-physical primaries which would, if added together, yield a color of the same hue as one specified by the corresponding (x,y) chromaticity coordinates. Note that the luminance information is lost when only the (x,y) coordinates are given. Where the X, Y, and Z tristimulus values are given, the luminance of the color is simply the Y value for the color. This particular set of imaginary primaries was chosen to have this property that Y represents all the luminance of the color and also to have the property that the color triangle defined by the X, Y, Z primaries encloses the entire spectrum locus. Therefore negative amounts of X, Y, or Z are never required to represent real colors as would be the case if real primaries were used.

The X, Y, and Z tristimulus values for a source with energy distribution $E(\lambda)$ is found by the following formulas.

$$X = \int_{\lambda 1}^{\lambda 2} E(\lambda)\,\bar{x}(\lambda)\,d\lambda$$

$$Y = \int_{\lambda 1}^{\lambda 2} E(\lambda)\,\bar{y}(\lambda)\,d\lambda$$

$$Z = \int_{\lambda 1}^{\lambda 2} E(\lambda)\,\bar{z}(\lambda)\,d\lambda$$

where λ_1 is lower limit of visible spectrum

λ_2 is upper limit of visible spectrum

and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the distribution coefficients shown in Figure 26.

The distribution coefficients $\bar{x}$, $\bar{y}$, and $\bar{z}$, define the amounts of each primary X, Y, and Z required to match any given spectrum color. These coefficients are obtained by linear transformation of the $\bar{r}$, $\bar{g}$, and $\bar{b}$ distribution coefficients which result from experiments with the amounts of real red, green, and blue primaries required to match spectrum colors. The $\bar{r}$, $\bar{g}$, and $\bar{b}$ distribution coefficients are not often used because negative amounts of the primaries are often required to match certain spectral colors as shown in Figure 27.

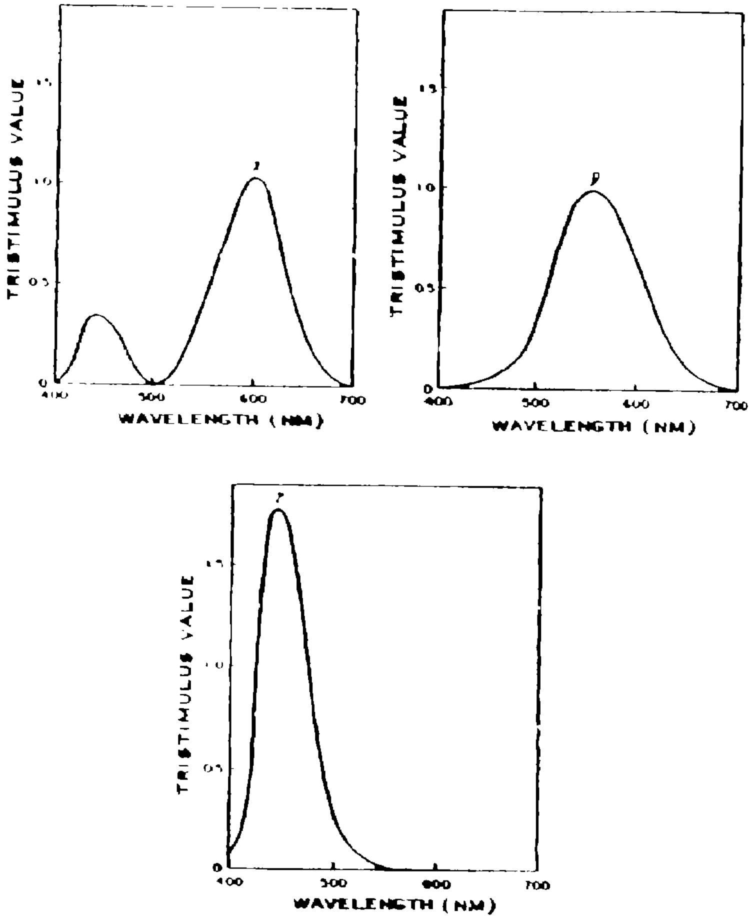


Figure 26 CIE $\overline{x}$, $\overline{y}$, $\overline{z}$, Mixture Curves (Distribution Coefficients or Tristimulus Values of the Spectrum)

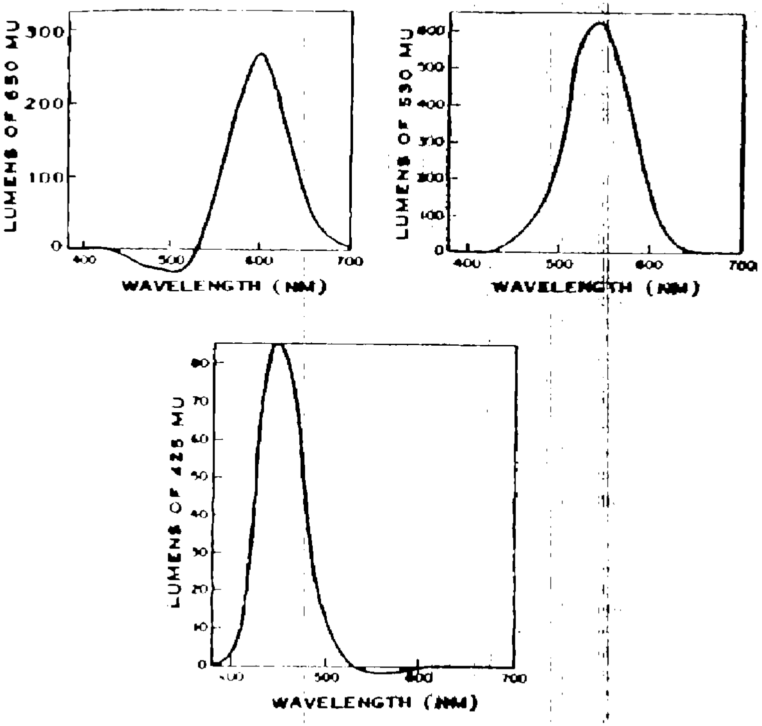


Figure 27 $\overline{r}\ \overline{g}\ \overline{b}$ ixture Curves

For the case of the CRT filter combination, the filter transmission is denoted by $t(\lambda)$ and the X, Y, Z tristimulus values are

$$X = \int_{\lambda 1}^{\lambda 2} E(\lambda)\ t(\lambda)\ \bar{x}(\lambda)\ d\lambda$$

$$Y = \int_{\lambda 1}^{\lambda 2} E(\lambda)\ t(\lambda)\ \bar{y}(\lambda)\ d\lambda$$

$$Z = \int_{\lambda 1}^{\lambda 2} E(\lambda)\ t(\lambda)\ \bar{z}(\lambda)\ d\lambda$$

Since there are no simple analytical expressions for the distribution coefficient curves, the X, Y, Z values are calculated by means of numerical integration.

We divide the CRT spectrum $E(\lambda)$ into narrow sections (5 nm to 10 nm (nanometer) wide) and form the sums

$$X = \sum E(\lambda)\ t(\lambda)\ \bar{x}(\lambda)$$

$$Y = \sum E(\lambda)\ t(\lambda)\ \bar{y}(\lambda)$$

$$Z = \sum E(\lambda)\ t(\lambda)\ \bar{z}(\lambda)$$

Where the values of $E(\lambda)$, $t(\lambda)$ and $\bar{x}, \bar{y}$, and $\bar{z}$ are taken at the center of the 5 to 10 nm intervals.

Since the widths of the intervals are not included in these summations, the X, Y, Z values obtained are proportional to the true X, Y, Z values. For most colorimetric calculations, this makes no difference in the result as the x, y, and z coordinates are found by ratios of X, Y, Z. Even in calculating the amounts of each phosphor needed in the mixture only the ratios are critical.

3.3.2.2 Programs for Calculating CIE Coordinates. A Fortran IV program, named COLOR 3 was developed for use on Philco-Ford's in-house time sharing computer system. The program accepts as input data the values of the input source spectrum (normalized to a maximum amplitude = 1) at 5 nanometer intervals from 380 nm to 780 nm. Also, any arbitrary filter transmittance spectrum can be input to the program. The outputs are the x, y, z chromaticity coordinates of the light produced by the source-filter combination. Also, a value Y which is proportional to the Y tristimulus value of the color is computed. This program and detailed instructions are found in Appendix IV.

For the narrow peaks of the red and green phosphors, a K&E polar planimeter was used to find the area under the spectrum curve within a 5 nanometer interval. These values were then used as inputs to the program COLOR 3. These equivalent spectrums are below in Figures 28 and 29.

3.3.3 Procedure for Selecting Phosphor Ratios and Color Wheel Filters

The phosphor ratios and the positions of the color filters in the visible spectrum were calculated by a straight forward iterative procedure using several additional programs which are summarized below.

"ADDER" - Adds together any number of components to form a composite output spectrum called "SRGB." Each component can be multiplied by an arbitrary constant before addition is performed.

"COLOR 3" - Described in paragraph 3.3.2.2 finds the chromaticity coordinates and luminance of the light from an arbitrary spectrum and color filter combination.

"RATIO" - Given the chromaticity coordinates of three primary colors and the chromaticity coordinates of a resultant color, the program computes the ratios of the luminances of each primary to the luminance of the resultant necessary to match the resultant with some mixture of the primaries.

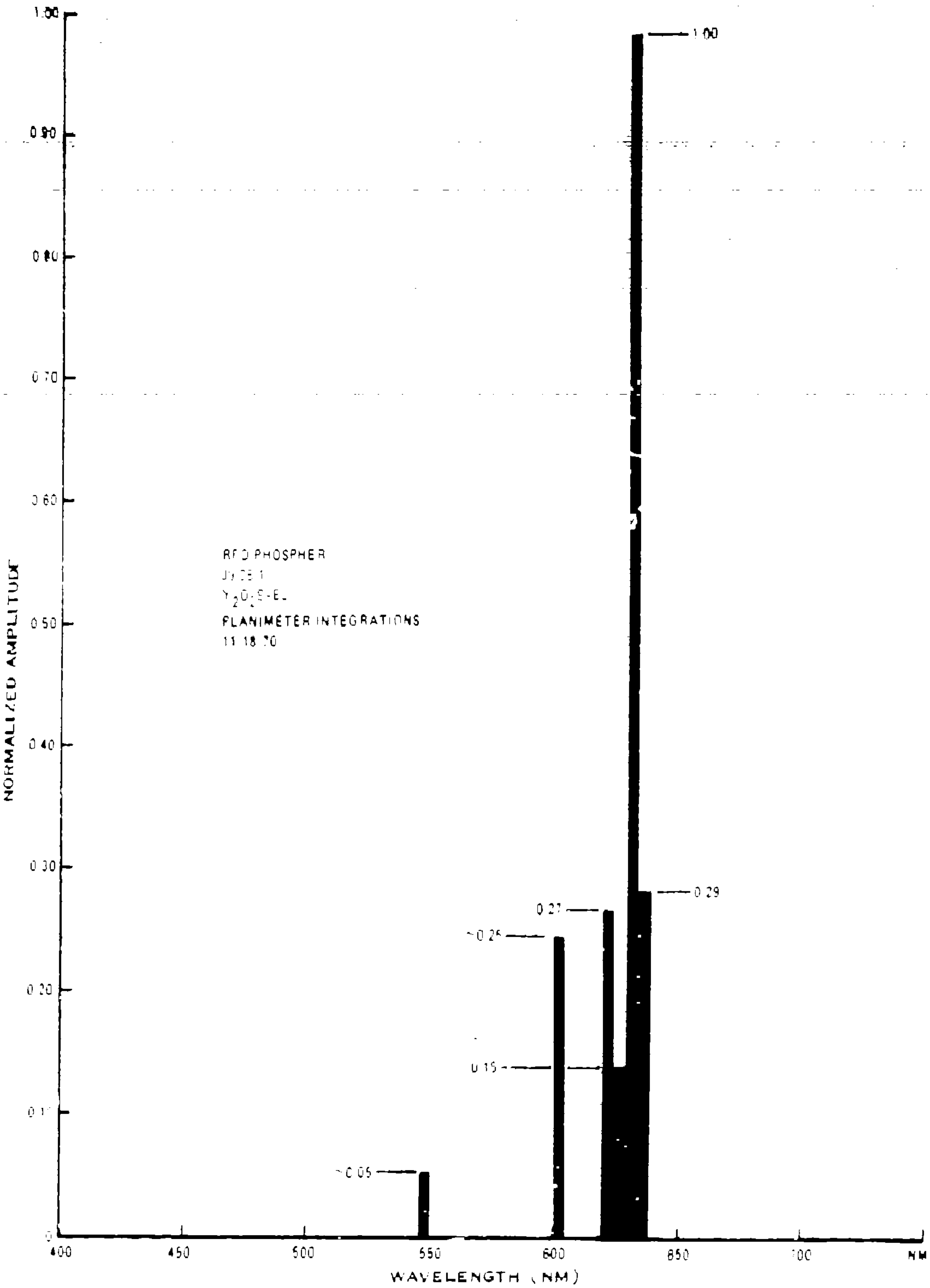


Figure 28 Red Phosphor

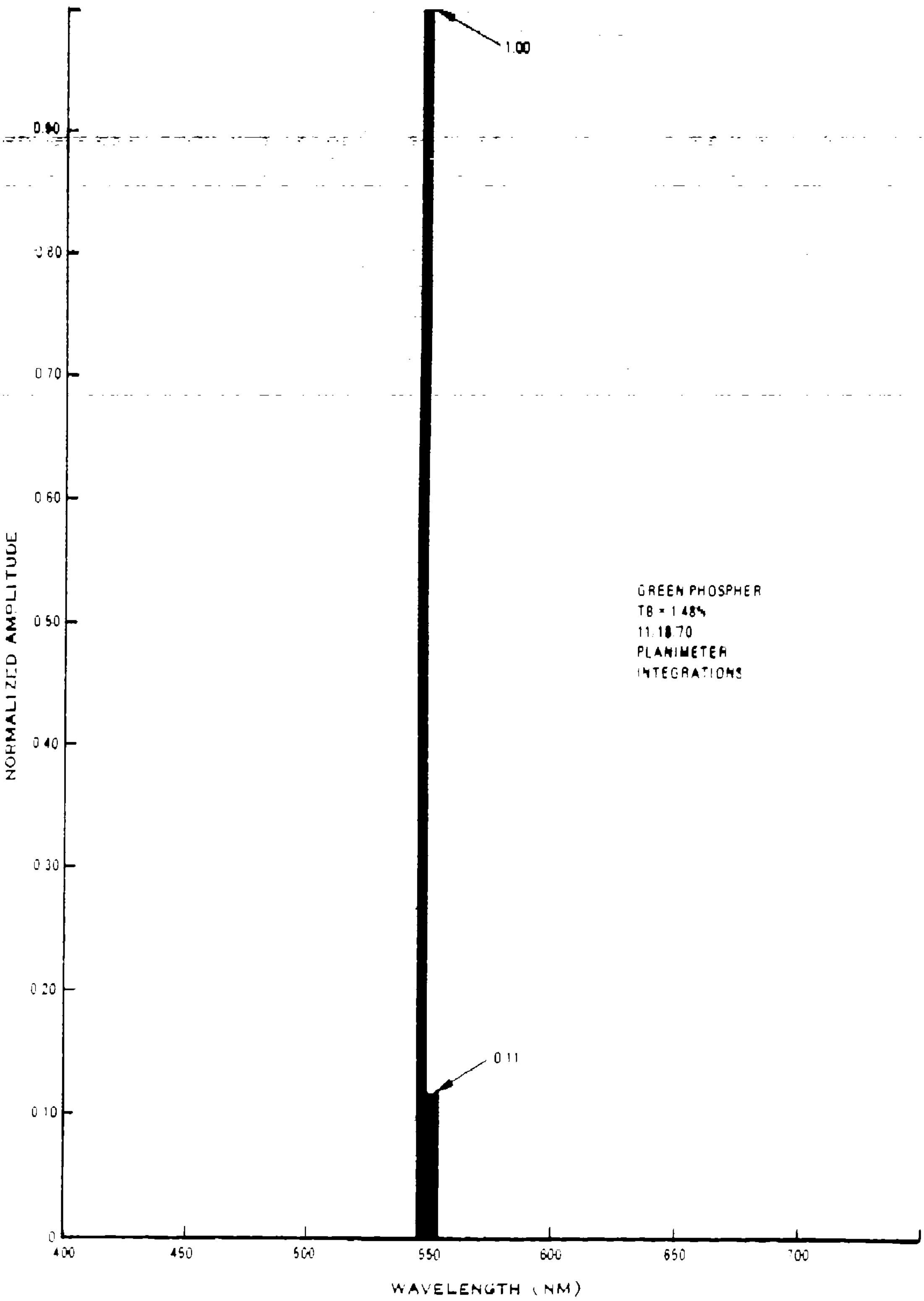


Figure 29 Green Phosphor

"SHIFT" - Given the input transmission spectrum of an arbitrary filter, a new filter transmission spectrum is created which is the old spectrum shifted right or left (to longer or shorter wavelengths) by a specified number of nanometers.

"XYL" - This program accepts the chromaticity coordinates and the luminance of any number of primaries and computes the chromaticity and luminance of the resultant color derived by adding the component colors together.

The first step in the specification of the phosphors was to choose three standard Bausch and Lomb interference filters which had bandwidths and band edges in approximately the correct locations as determined by inspection of the composite phosphor spectrum. Figure 30 shows the three filters superimposed on the composite phosphor spectrum. The red filter is named BAURED (abbreviation of Bausch and Lomb red) and the other two filters are named similarly BAUBLU and BAUGRN. The narrowband filter shown with a dotted line and centered at 550 nm is named BAUGRN 30 because it is the same filter as BAUGRN but is shifted 30 nm to the right. This convention is followed throughout.

Inspection of Figure 30 immediately shows that BAUGRN should be shifted right about 30 nm, thus we use the program "SHIFT" and derive BAUGRN 30. The next step is to form a composite spectrum of the various phosphor components. The first cut is called SRGB (abbreviation of spectrum-red, green, blue) and is a straight addition of the blue phosphor (BLUESIL), the green phosphor (GSPEC) and the red phosphor (RSPEC), all with unit peak amplitudes. Then using Color 3, the chromaticity (x, y) coordinates of SRGB and BAUBLU, SRGB and BAUGRN 30, and SRGB and BAURED are computed and plotted as shown in Figure 31.

Figure 30 again tells us that the long tail on the blue silicate (BLUESIL) phosphor is passing through BAUGRN 30 and destroying the purity of the green primary. Further inspection of Figure 30 shows that the amount of the blue phosphor (BLUESIL) affects the green purity but not the red purity to any significant extent. Also, the varying of the amount of red phosphor affects none of the purities and varying the amount of green phosphor affects the green purity but not the red or blue purities. It was then obvious that the ratio of green phosphor to blue phosphor would have to be increased to improve the green purity. It would also have been possible to decrease the bandwidth of BAUGRN 30 somewhat, but this filter

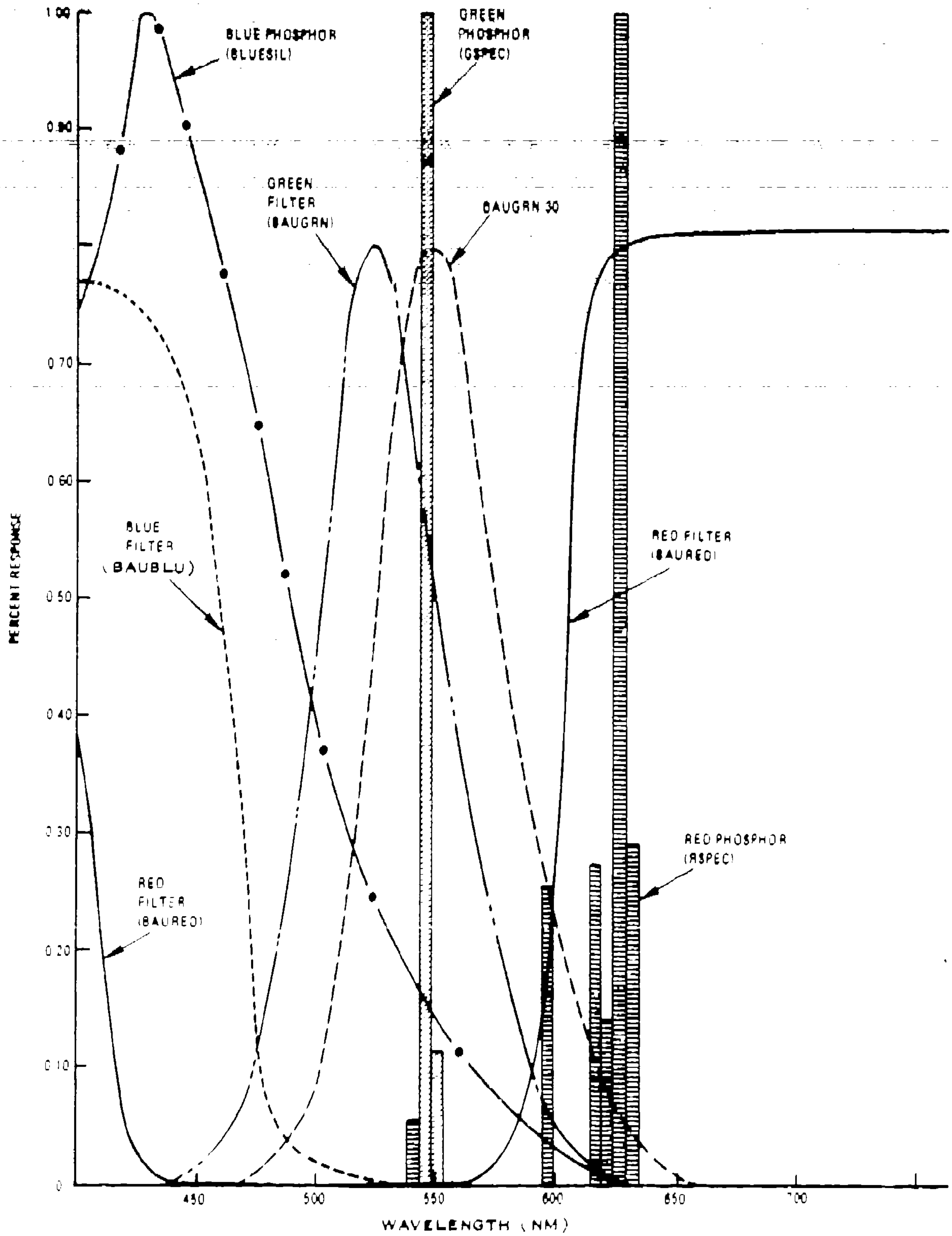


Figure 30 Phosphor Spectrums and Filter Curves

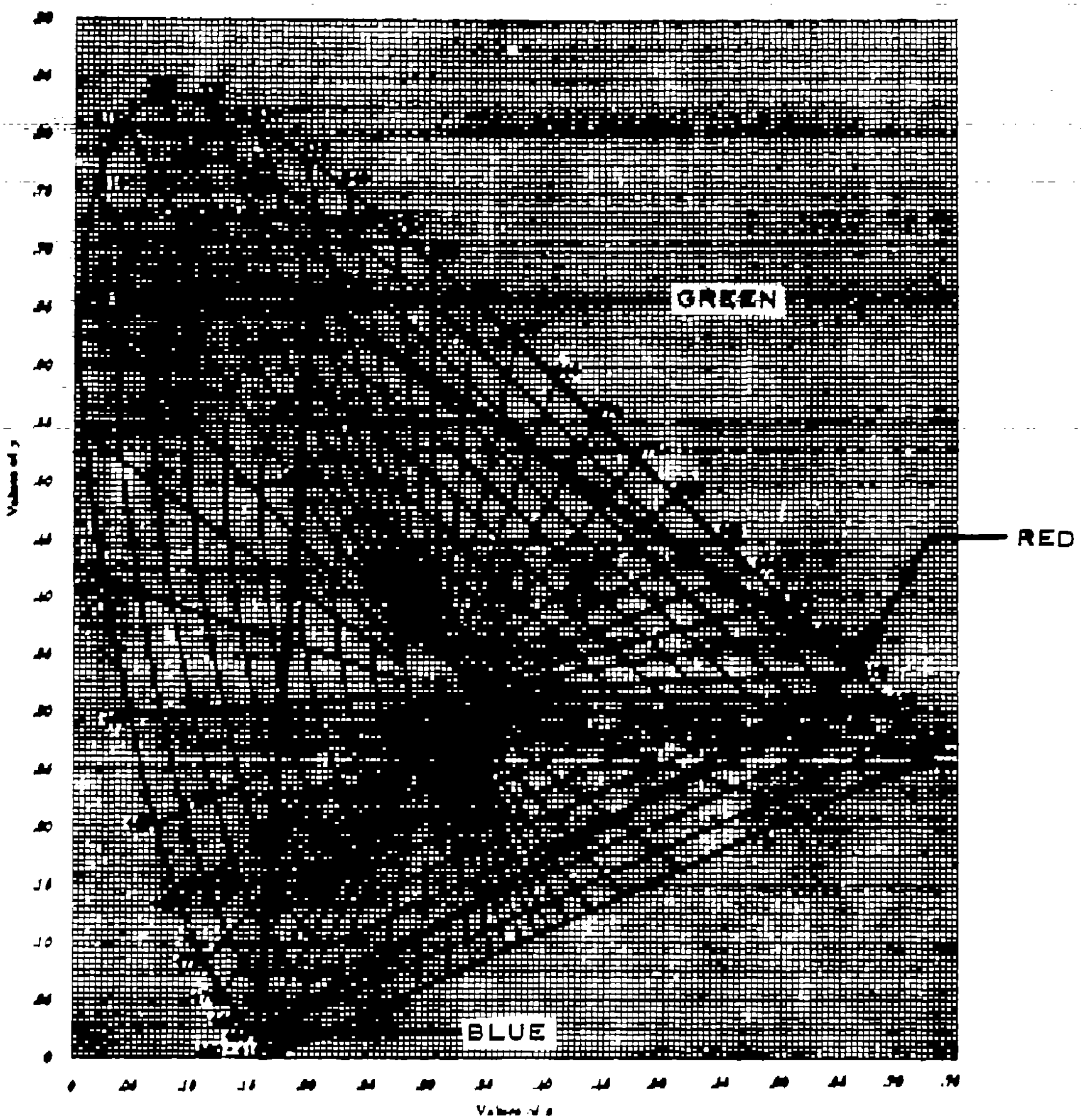


Figure 31 First Calculation of Primaries for SRGB Spectrum

was already near the practical lower bandwidth limits for interference filters. The next step therefore was to compute a new input phosphor spectrum (SRB) which contained no green phosphor at all. SRB was run against BAUBLU, BAUGRN 30, and BAURED to determine the primaries (R, G, B) shown in Figure 32.

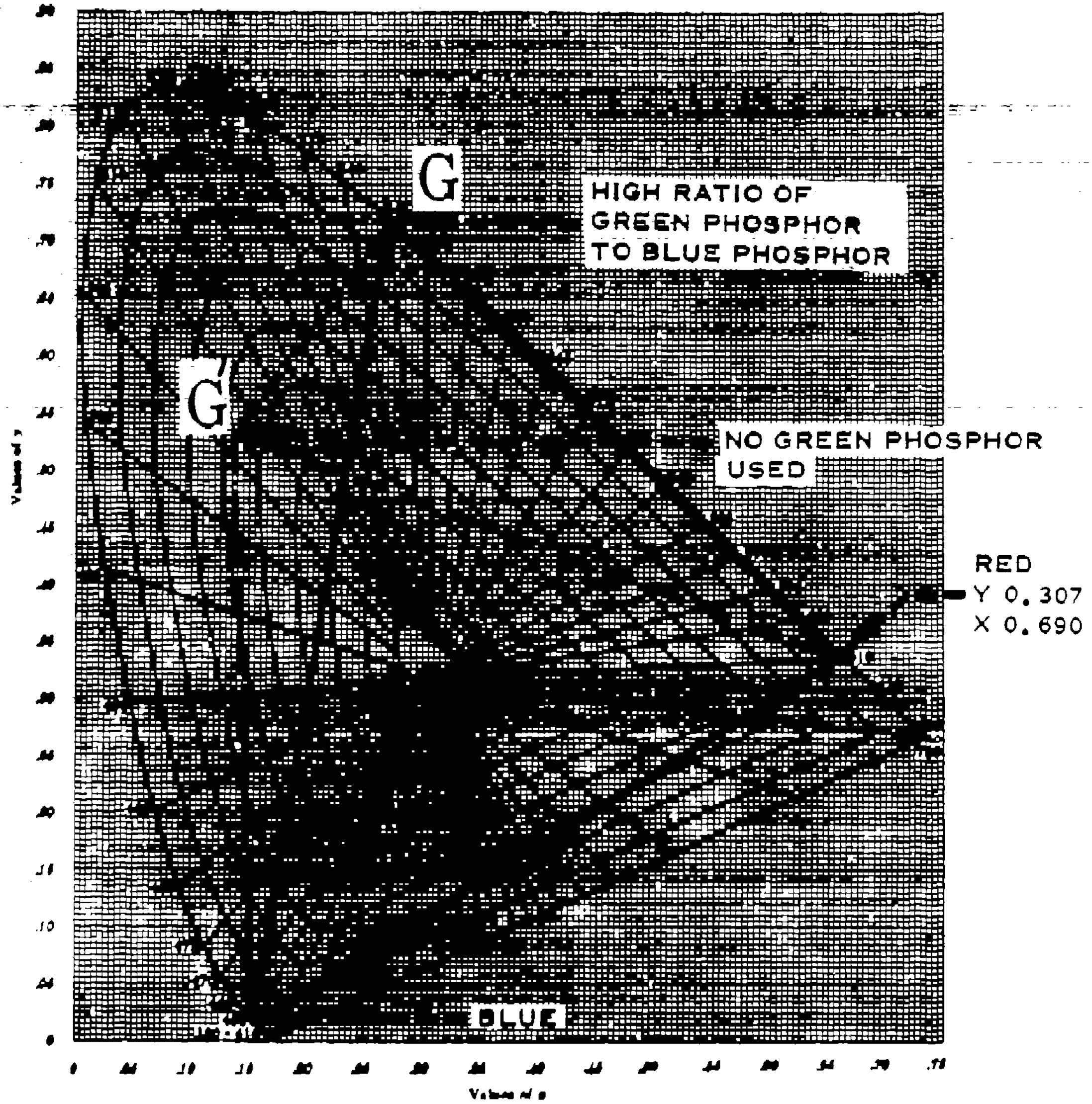


Figure 32 Primaries for SRB and SRG Spectrums

Now we form another spectrum which contains no blue phosphor, just red, and green (SRG) and run this against the filters BAUBLU, BAUGRN 30, and BAURED, using COLOR 3 to obtain the primary chromaticities. These primaries (RGB) are also plotted in Figure 32 and from the linear properties of color addition we know that spectrums consisting of all the phosphor components will produce green primary chromaticities which lie somewhere on the line connecting G' and G, depending on the proportions of blue and green in the mixture.

Next, the chromaticity coordinates of the point is obtained where the line connecting G and G' and the 90% purity contour intersect (x = 0.25, y = 0.70). This data is then inserted with the chromaticity coordinates of the points G and G' into the program XYL to permit determination of the ratio of GSPEC to BLUESIL required to yield a purity of 90% for the green primary. XYL is used by inputing the G and G' (x, y) coordinates with some assumed luminance for each color. The resultant chromaticity is then plotted on the CIE chart and further trials are made until the desired resultant chromaticity is achieved. For the particular filters specified, the results were

PRIMARY		x	y	Luminance
G	(no blue phosphor)	0.270	0.720	1.0
G'	(no green phosphor)	0.235	0.500	10.0
90%	purity green primary	0.265	0.695	11.0

This result tells us that the green phosphor to blue phosphor ratio must be at least 10:1 to get 90% green purity through the green filter. The trial and error procedure followed with the program XYL could be eliminated by writing a new program to find the required ratio of two primaries necessary to obtain a given resultant. This was not done because the trial and error procedure converges rapidly and is quickly done on the time sharing computer system.

After the blue-green ratio was determined, a new SRGB spectrum was created with "ADDER" which had the proper green to blue ratio. The primaries at this point were computed using BAURED, BAUGRN 30 and BAUBLU filters.

	x	y
R	0.646	0.320
G	0.265	0.692
B	0.160	0.015

The blue primary was too weak and had a primary hue of about 440 nm which was too far toward the violet. A new filter BAU500 was developed which gave a much better luminance at about 90% purity with a dominant wavelength of about 465 nm.

The final set of primaries was then

	x	y
Red	0.646	0.320
Green	0.267	0.690
Blue	0.153	0.068

with the color wheel filters BAURED, BAUGRN 30, and BAU500. Other trials were made in which the blue, green, and red filters were shifted back and forth, but the set of filters last specified gave the best results.

Figure 33 shows the final filter locations superimposed on the normalized phosphor spectrums. The last task in specifying the phosphor was to calculate the luminance ratios which should be observed when the luminance in each of the primaries was compared to the total luminance from the CRT. For the final set of primaries "RATIO" was used to find the luminance ratios needed to match Illuminant "C". These were approximately:

$$\frac{Y_r}{Y_t} = \frac{Y_{red}}{Y_t} = 3.4 \qquad \text{where } Y_t = \text{total luminance}$$

$$\frac{Y_g}{Y_t} = \frac{Y_{green}}{Y_t} = 9.1$$

$$\frac{Y_b}{Y_t} = \frac{Y_{blue}}{Y_t} = 1.4$$

but the spectrum SRGB, in which each of the phosphors has been properly scaled to give the correct chromaticities when through the various filters, yields luminance ratios:

$$\frac{Y'_r}{Y_t} = 1.2$$

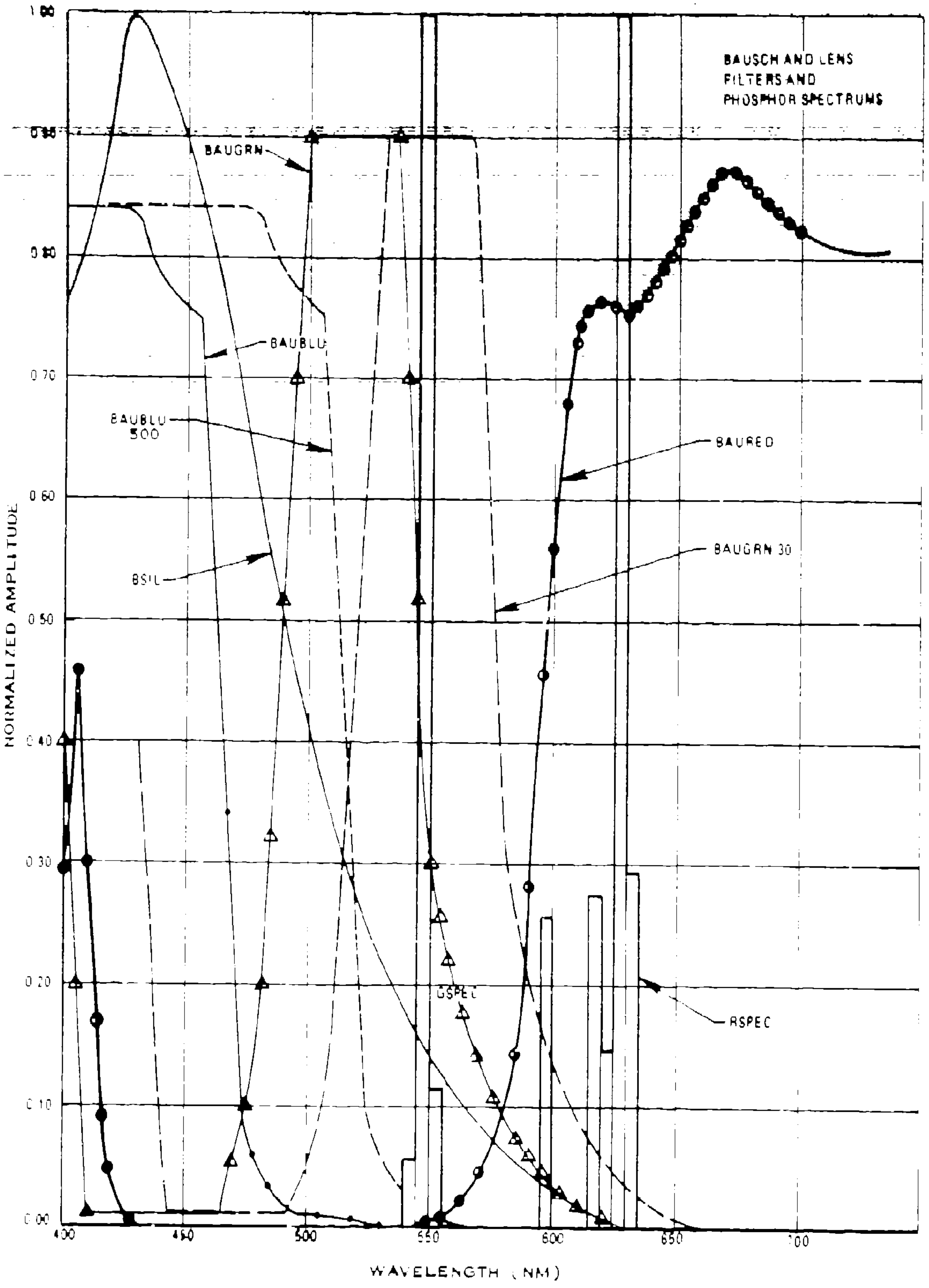


Figure 33 Bausch and Lomb Filters and Phosphor Spectrums

$$\frac{Y'_g}{Y_t} = 18.4$$

$$\frac{Y'_b}{Y_t} = 1.4$$

The ratio Y_g/Y_b to yield white = 6.5
The ratio Y'_g/Y'_b to yield good green purity = 13.0

Thus, we see that we must have much more green than required for maximum balanced white. This is a compromise made necessary by the broadband spectrum of the blue phosphor. If a narrow-band blue phosphor becomes available, the brightness of both the red and the blue can be increased for a greater white brightness. For an assumed 10,000 footlambert maximum CRT luminance, the luminances of each primary as measured through each color filter are:

Red	(measured through BAURED)	=	1500 footlamberts
Green	(measured through BAUGRN 30)	=	7900 footlamberts
Blue	(measured through BAU 500)	=	600 footlamberts

The maximum white brightness possible with this mixture is approximately 6000 footlamberts for the maxiumum luminance through all the filters of 10,000 footlamberts.

3.3.4 Summary of Trade-offs in Phosphor Selection and Color Wheel Filter Specifications

- The blue phosphor was broadband, therefore, the amount of the green phosphor had increased above the amount required to yield a balanced white.

- Since the maximum output of the CRT was estimated at 10,000 footlamberts, only 600 footlamberts of the blue could be used. About 4 times this amount of blue is required to achieve the minimum of 15 footlamberts on the display screen.

3.3.5 CRT Phosphor Specifications

White Brightness. 10,000 footlamberts at writing speed of 290,000 inches per second with simultaneous requirement that line width not exceed 0.003 inches. (Test conditions 3.1" x 3.1" raster, 1000 lines/frame at 180 fields per second).

Mix

Red Phosphor	1500 footlamberts @ 630 nanometers
Green Phosphor	7900 footlamberts @ 530 nanometers
Blue Phosphor	600 footlamberts @ 470 nanometers

Aluminized Screen

Decay Characteristics. (persistence)

Red	Down to 1%* within 5.5 ms
Green	Down to 1%* within 5.5 ms
Blue	Down to 1%* within 5.5 ms

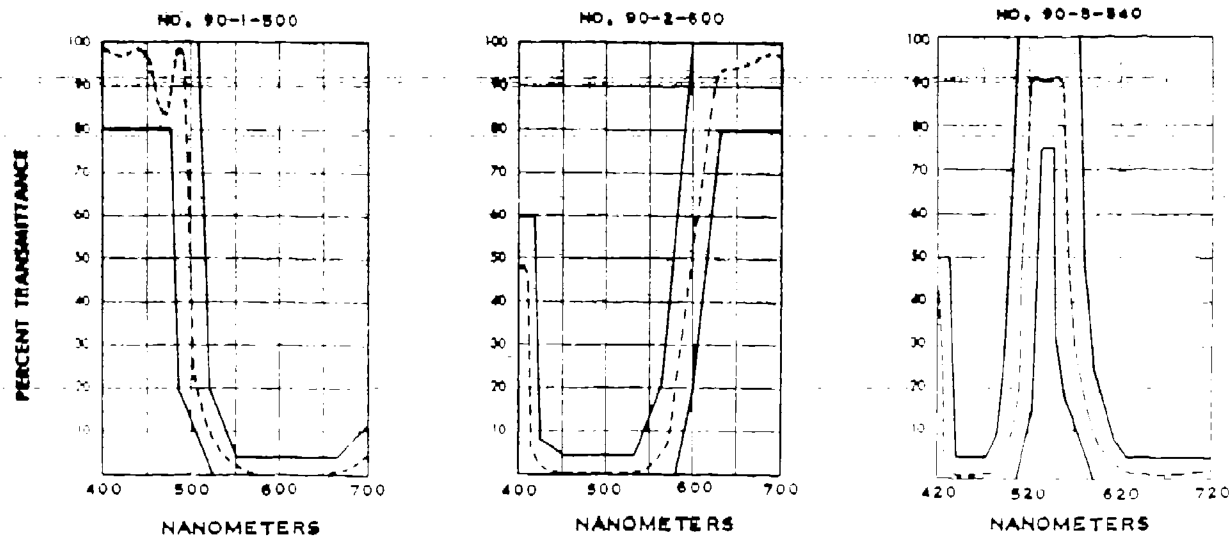
*Phosphors down to = 10% in 5.5 ms may be acceptable if others are not attainable.

Thomas Electronics was supplied with three Bausch and Lomb interference filters with the required passbands and edges. These filters were:

	Bausch and Lomb filter
Red	90-2-600
Green	90-5-540
Blue	90-1-500

3.3.6 Color Wheel Filter Specifications

The specified filters are those Bausch and Lomb filters listed above. The spectrum limits of these three filters as shown in Figure 34.



Blue Filter　　Red Filter　　Green Filter

Figure 34 Bausch and Lomb Filters

Figure 35 shows all of the filters superimposed on the same graph for ease in seeing the relative positions of the filters. These specifications were submitted to Bausch and Lomb for fabrication of the color wheel which is described in Section 5.2 (Figure 49 shows the spectral response.)

3.4 AREAS FOR FURTHER INVESTIGATION

3.4.1 Phosphors

One very worthwhile effort in order to improve the Real Time Improved Color Image Display would be the investigation and development of new rare earth phosphors. In particular, a good blue phosphor with a spike output around 470 nm would significantly improve the on-screen color brightness of the display. Another approach still pertaining to the rare earth phosphors, is to find a white or near white rare-earth phosphor with widely separated narrow-band outputs similar to that shown in Figure 36. This phosphor has unwanted output at 590 nm and a fairly small output at 620 nm, but has good green at 545 nm and good blue response at 490 nm. The relative amplitude of the peaks can be changed by varying the doping levels and the processing; and, as a group, the rare-earth phosphors are efficient and reasonably linear. It would seem worth the effort to do further investigation in this area.

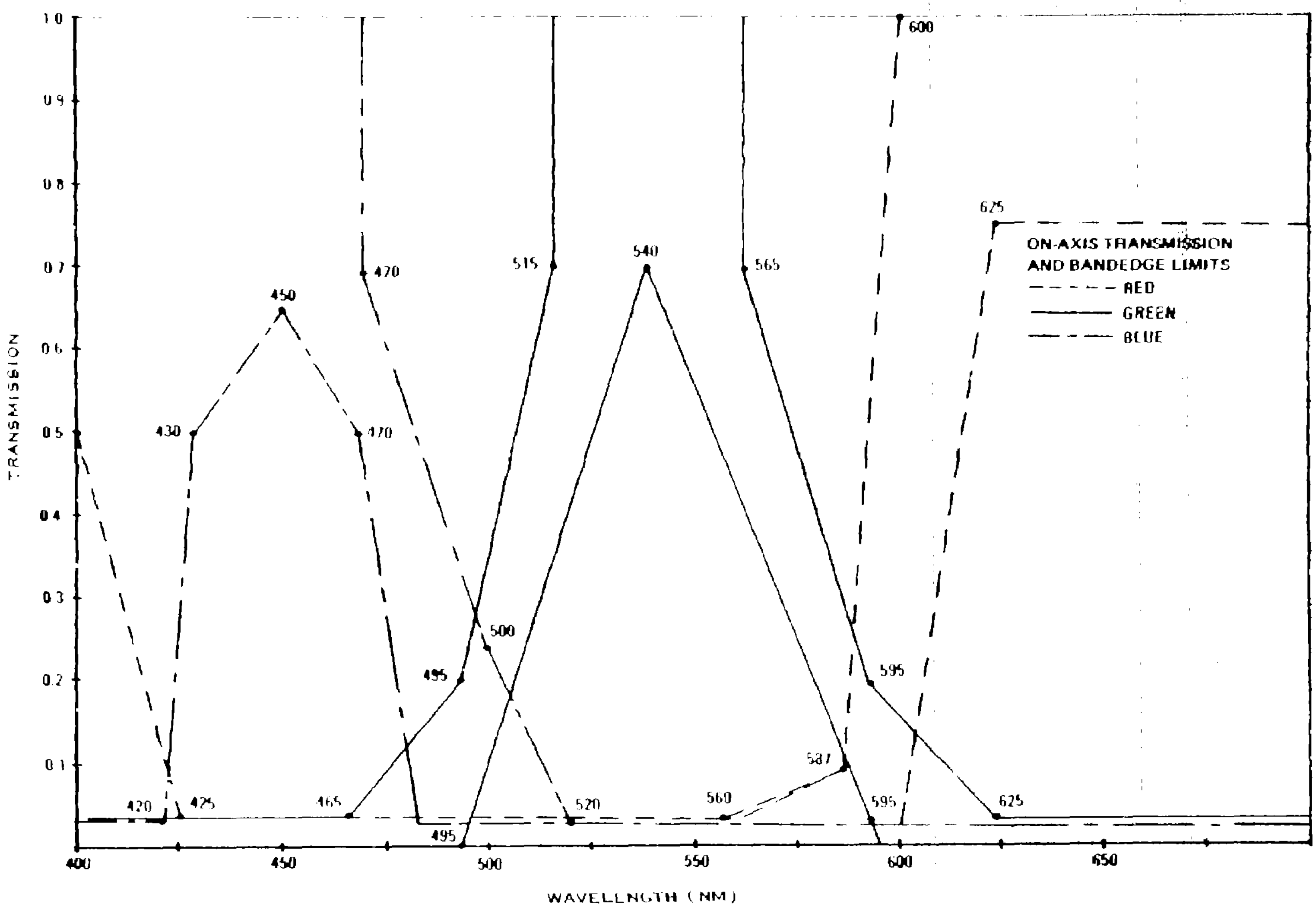


Figure 35 Filter Characteristics

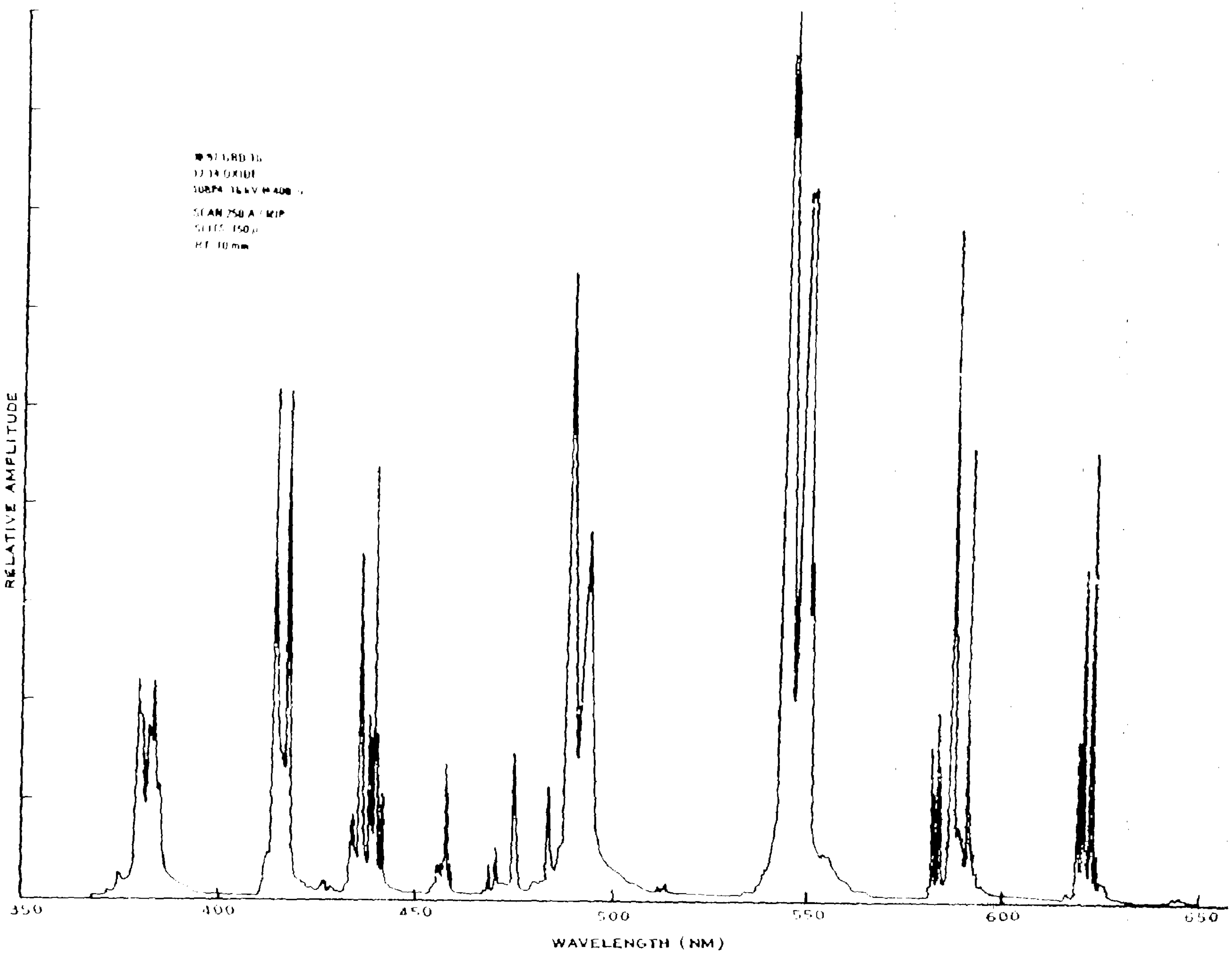


Figure 36 White Rare Earth Phosphor

3.4.2 Variation of Phosphor Ratios

For many alphanumeric and graphic applications, the brightness of the individual colors is more important than the ability to create highlight white where the percentages of red and blue are quite low compared to the percentage of green. Therefore, for these applications, the white brightness could be decreased to a level near that of the component red, green, and blue brightnesses. This is easily done by decreasing the amount of green phosphor and increasing both red and blue. Further study should be undertaken to determine the optimum phosphor ratios and consequently the component color brightness ranges for displays intended only for graphic and alphanumeric use.

3.4.3 Color Filter Characteristics

A common comment of persons observing a color display used for graphics, etc. is that the red and blue colors are too dim. As mentioned above, the phosphor ratios can be changed to somewhat improve this situation, but, even more important, both the filter and phosphor characteristics can be changed to yield primaries which are less saturated than those requested in the Wright-Patterson specifications.

A study on the comparison of saturated low brightness primaries against less saturated higher brightness primaries could be conducted. For non-pictoral information, the less saturated colors may be more satisfactory.

3.5 SUMMARY ON DESIGN OF CRT PHOSPHOR COLOR FILTER COMBINATIONS

The method used to design the CRT phosphor-filter combinations has been described above. The method is iterative and does not seem to allow a closed form solution; however, convergence is rapid for most problems.

A prototype tube was built by Thomas Electronics using the phosphors and phosphor ratios chosen above. The operation has been quite satisfactory from all viewpoints and is described in Section 4.0 (CRT specifications) and Section 2.0 (Test results for completed display mix).

SECTION 4

CRT SPECIFICATIONS

Many parameters of the CRT were important for the intended field sequential application. Two major areas are:

- Optical-Mechanical parameters
- Electrical parameters.

Examples of the opto-mechanical parameters were the size of the CRT and the optical configuration. For electrical parameters, there were the focusing method, the deflection method, anode voltage, deflection angle and others to consider.

All of the parameters had to be considered in view of the many system restraints imposed by the specifications. The restraints that apply to the CRT are discussed in Section 4.1. The design specifications are developed in Section 4.2, CRT specifications, and test results are included in Sections 4.3 and 4.4.

4.1 SYSTEM SPECIFICATIONS

4.1.1 Color Purity and Color Gamut

The phosphor considerations are covered in Section 3.

4.1.2 Display Brightness and Image Size

The specifications require a 14" by 14" image on the viewing screen. Since a field sequential approach was followed, it was necessary to have as small a CRT as possible both from the standpoint of building suitable projection lenses and from the standpoint of conserving space. A large CRT would require a large bulky color wheel unless some type of relay lens system

were employed which would in turn seriously reduce the light efficiency. The brightness requirement of 75 footlamberts on a 14" by 14" screen meant that a low f-number lens would be required which in turn dictated that a precision flatfaced CRT must be used to match this lens.

The screen brightness is calculable by the following formula

$$B_s = \frac{BT_L\, T_F\, T_M^{\,2}\, G}{4(M+1)^2 f^2 + M^2}$$

where

B_s = Screen brightness in footlamberts

B = Brightness of CRT in footlamberts

T_L = Transmission of lens 0.75

T_F = Transmission of color wheel = 0.31

T_M = Transmission of optical mirror = 0.94

G = Gain of rear-projection screen = 2.5

M = Magnification (14" from 3.1") = 4.5

F = f-stop of projection lens

We can solve for the f-number required where the screen brightness is 75 footlamberts and the CRT brightness is 15,000 footlamberts.

$$B_s 4(M+1)^2 f^2 = BT_L\, T_F\, T_M^{\,2}\, G - B_s M^2$$

$$\text{implies } f^2 = \frac{BT_L\, T_F\, T^2_M\, G - B_s M^2}{4(M+1)^2\, B_s}$$

$$f = \left[\frac{15\times10^3(0.75)(0.31)(0.94^2\ 2.5 - 75(4.5)^2}{4(4.5+1)^2\ 75}\right]^{1/2} = 0.83$$

Figure 37 shows in graphical form the relationship between the CRT brightness, the screen brightness and the lens f-number for the conditions noted.

At the time the bid was let for the projection lens, the best lens that the optical companies thought could be built with good resolution and color correction was about f/1. As Figure 37 shows, the maximum screen brightness for the f/1 lens with a 15,000 footlambert CRT brightness is about 55 footlamberts. Today, the computer-aided optical design programs and the designers skills have improved sufficiently that f/0.8 lenses appear possible. Diffraction Optics of Mountain View, California has indicated that they would be willing to bid for construction of an f/0.8 lens with suitable resolution and color correction for the Real Time Improved Color Image Display. With this new f/0.8 lens which has recently become feasible, the brightness of the display would reach 78 footlamberts using a screen gain of 2.5.

4.1.3 Modulation Transfer

The AFAL specifications requested a 50% modulation transfer factor in both the horizontal and vertical dimensions at 1000 TV line resolution. The modulation factor of 50% should thus be obtained with a resolution of 500 line pairs per screen height or width. For a 50% spot width equal to 3 mils, the modulation transfer factor can be calculated by the formula below for an assumed gaussian spot. Even though the projection CRT spot is not truly gaussian, the approximation is fairly good for initial estimates.

$$M = \frac{F(0) - F(D/2)}{F(0)}$$

where

$$F(x) = \sum_{-\infty}^{+\infty} \exp\left[\frac{-2.76}{W^2}(x-ND)^2\right]$$

$$F(0) \cong \sum_{-\infty}^{+\infty} \exp\left[-2.76N^2\ (D/W)^2\right]$$

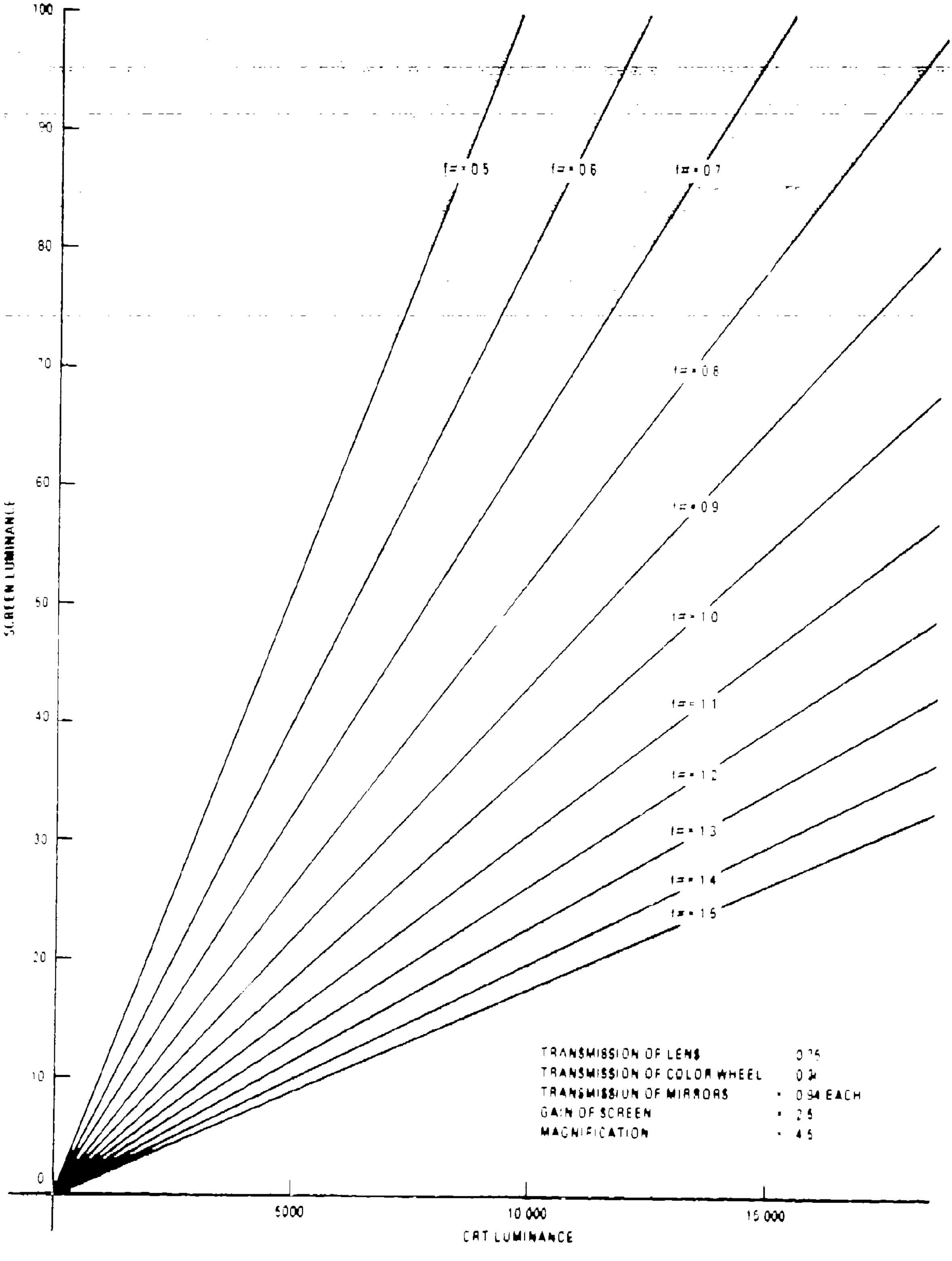


Figure 37 Screen Brightness vs CRT Brightness and f#

$$F(D/2) \cong \sum_{-\infty}^{+\infty} \exp\left[\frac{-2.76\ (D/2)\ -ND)^2}{W^2}\right]$$

and D = the separation of the gaussion spots

W = the 50% width of the gaussion spots

A good approximation to the infinite sums is to sum only 10 gaussians and calculate the modulation at various width to separation ratios for the centermost gaussian. Figure 23 is a graph of the results obtained for width to separation ratios of 0 to 1.4. One curve is calculated for using the 2σ width (60.6 amplitude width) and the other for the 2.35σ width (50% amplitude width). These two curves can be used to rapidly estimate the modulation resulting from various spot sizes. Since the limiting contrast resolution of the eye is about 2% (Conrady criterion) the 2σ curve tells us that the shrinking raster technique yields spots widths near the 2σ width rather than the 50% (or 2.35σ) width. The conclusion reached by noting that 2% modulation is obtained at a width-to-peak ratio of about 1.03:1 on the 2σ curve. Now we estimate the percent modulation at 500 line pairs per 3.1 inches and a shrinking raster spot size of 3 mils.

Separation of gaussians = $D = \frac{3.1}{500} = 6.2$ mils

60% width = 3 mils

60% width-to-peak separation ratio = $\frac{3.0}{6.2} = 0.484$

Using Figure 38:

Modulation = 76% in the center at 1000TV lines

The 500 line pairs per 3.1 inches is used since a 3.1-inch raster is the largest square raster that can be used on a 5" CRT without bringing the corners of the raster too close to the edge of the faceplate.

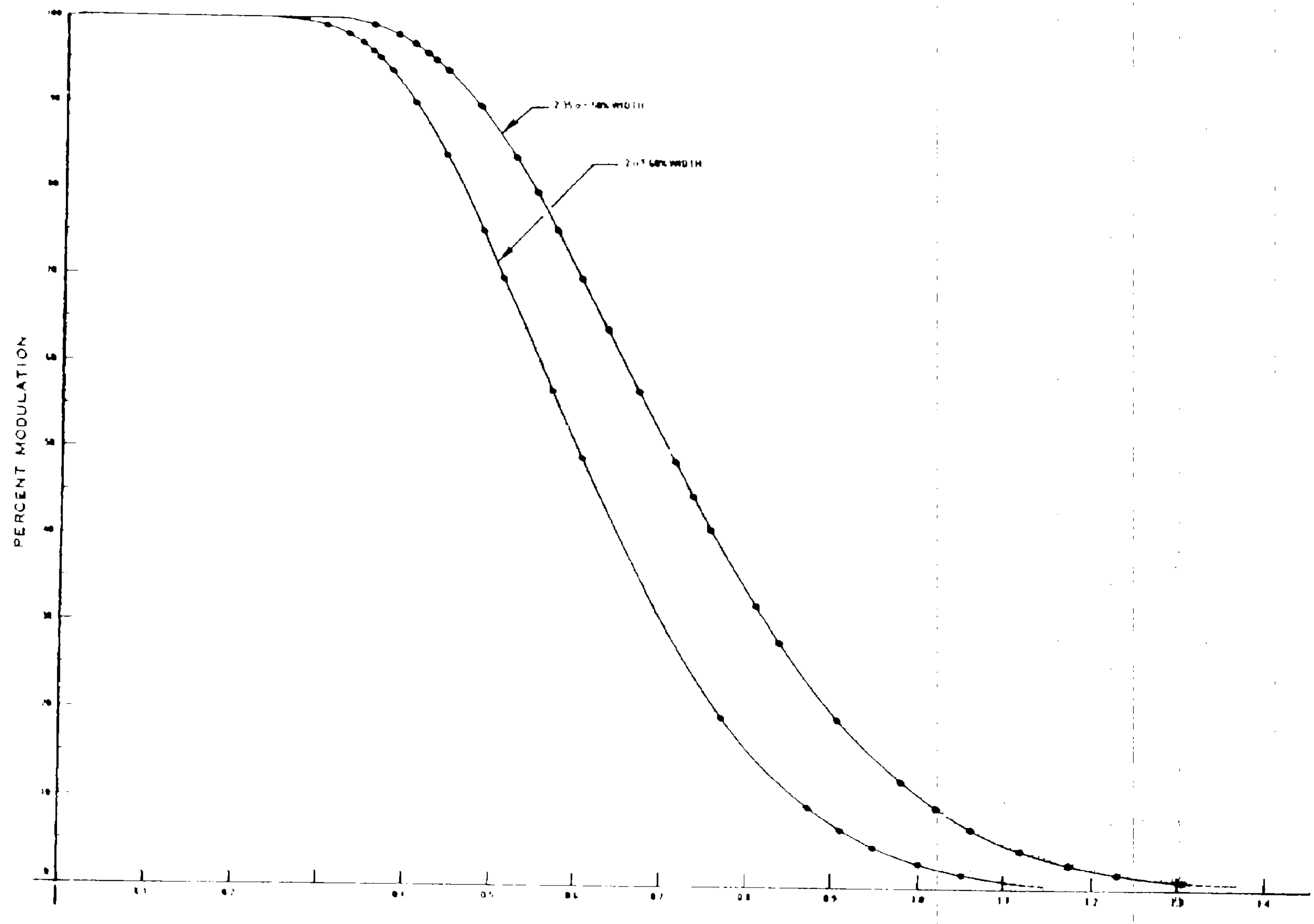


Figure 38 Modulation vs Peak Separation

With dynamic focus, the spot growth from the center to the edge of the CRT can seldom be held to less than 30% *. This performance is verified by Philco-Ford experience with projection displays utilizing dynamic focus.

Based on an estimated 30% spot growth in the corners, the spot size at the 60% point can be written W' = 1.3W. Recalculating the modulation at spacing d = 2W with width W' = 1.3W we have

$$\text{separation of gaussians} = D = \frac{3.1''}{500} = 6.2 \text{ mils}$$

$$30\% \text{ width} = 3.9 \text{ mils}$$

$$60\% \text{ width-to-peak separation ratio} = \frac{3.9}{6.2} = 0.63$$

using Figure 4-2

Modulation = 44% in the corner at 1000TV lines

Since the predicted depth of modulation of the lens was at least 85% over the entire field at 1000TV lines, we can estimate the center and edge modulation on the screen by multiplying together the depth of modulation numbers for the lens and a 5" CRT.

It should be noted that the above calculations are examples for systems with gaussian responses for the spot contour. The actual situation is that the spot is somewhat flattened on top and has steeper sides than the conventional gaussion spots. This implies that the actual results would be better than those of Table III if not reduced due to other factors such as yoke fringe fields, ripple on the high voltage power supply or jitter in the deflection waveforms.

TABLE III

DEPTH OF MODULATION

Modulation	CRT	Lens	Total
CENTER	76%	85%	65%
EDGE	44%	85%	32%

* White, L. E., Electronic Equipment Engineering, Vol II, No. 4, 1963

4.1.4 Electrical Parameters of the CRT

The important characteristics of the CRT are:

1. Focus method
2. Deflection method
3. Deflection angle
4. Accelerator voltage
5. Grid number 1 cutoff voltage
6. Modulation voltage
7. Line width
8. Spot position
9. Accelerator

The focus method for projection CRTs is almost invariably magnetic for two major reasons. First, the magnetic lens formed by the magnetic focus coil is much larger in diameter than any electrostatic lens could be. Therefore, a magnetic lens has higher current handling capability with lower distortion than an electrostatic lens. Secondly, a magnetic lens will generally produce a smaller spot than an electrostatic lens. Some disadvantages of magnetic focus are that dynamic focus is hard to perform (but is even more difficult for all electrostatic methods) and the focus coil is heavy, often weighing more than 2 lbs. Additionally, the focus coil must be precisely aligned with the axis of the electron beam and this alignment maintained in the presence of vibration and shock. In spite of these disadvantages, magnetic focus has been proven by experience at Philco-Ford to give the best results for high resolution projection CRTs when compared with the electrostatic alternative.

The deflection method is magnetic to avoid the high voltage levels and spot distortions caused by electrostatic deflection. Also, the deflection angle should be kept low to minimize deflection defocusing. Projection CRTs with 46° deflection angles have been used in several Philco-Ford projectors with good results.

A high accelerator voltage is desirable for achieving a high brightness at reasonably low beam currents. The light output for a properly designed screen varies as $L = KE^{1 \text{ to } 1.5}$

where E is the anode voltage, L is the luminance of the screen and K is the proportionality constant, where the beam current is kept constant. Some of the tradeoffs are that as the anode voltage is raised, there is more tendency for arcing to occur in the electron gun and the deflection currents required increase to higher values. Also, the glass in the CRT becomes more severely stressed in the dielectric sense and puncture of the faceplate and CRT neck become more common. Projection CRTs such as RCA's old 7NP4 operated at anode voltages of 75 kilovolts and highlight brightnesses of up to 30,000 footlamberts; however, these tubes were difficult to use because of the high voltages required. Present projection CRTs are built to operate with anode voltages of 40 to 50 kilovolts. This practice has resulted in reasonably high brightnesses (up to 18,000 footlamberts, depending on the writing speed) and ease of operation since the 40-50 kV anode voltage is relatively easy to work with.

Another important parameter of the CRT is the grid-to-cathode cutoff voltage and the related modulation voltage required to modulate the CRT to maximum brightness. For high resolution projection CRTs, the grid-to-cathode cutoff voltage should be kept as low as possible while still maintaining as high a beam current capability as possible in the CRT gun. The E_{gk} (grid-to-cathode) voltage should be low because we want the maximum bandwidth from the video amplifier and it is much easier to modulate 80 volts in 8 nanoseconds than to modulate 120 volts in the same 8 nanoseconds. A cutoff voltage of -80 to -110 volts was specified since this performance had been achieved with other 45 kV projection CRTs used by Philco-Ford. Simultaneously, an accelerator current capability of 2000 μa was specified.

The line width was specified at 0.003 inches as measured by the shrinking raster method. The tradeoffs involving the resolution are discussed in paragraph 4.1.2. This line width of 0.003 inches was the best performance we could obtain in a high brightness projection CRT.

The spot position was specified to guarantee that the focus coil could be aligned with the electron beam without the use of an excessive offsetting magnetic centering field which could cause spot astigmatism. Undeflected spot positions within a 3/8" radius circle located at the center of the CRT are fairly easy to correct with low intensity magnetic centering fields which do not significantly distort the shape of the electron beam.

4.1.5 Mechanical and Optical Parameters

These parameters concern only the faceplate of the CRT which is an optical element of the lens. For the purposes of the CRT specification, it was sufficient to specify the flatness of the surfaces to be within 0.005 inches RMS and to be parallel within 0.005 inches.

4.2 CRT SPECIFICATIONS AND STATEMENT OF WORK

The detailed CRT specifications are found in Appendix II.

4.3 TEST RESULTS FOR CRT

The parameters specified in the specification and statement of work were tested at Thomas Electronics, Wayne, New Jersey. The test results are listed in Table IV with explanatory notes on the next page.

The test results are discussed in paragraph 4.3.1.

4.3.1 Discussion of the CRT Test Results

The results achieved by Thomas Electronics are compared with the specifications in Table IV.

TABLE IV
CRT TEST RESULTS

Parameter	Specified	Test Result
Operating Conditions		
Accelerator voltage	40,000 volts	45,000
Grid no. 1 voltage (note 1)	-80 to -110 volts	-110 volts
Line width (note 2)	typical 0.003 inch	0.003 inch
Modulation	80 volts, max. (note 1)	80 volts
Spot position	within a 3/8"-radius circle (note 3)	within 1/8"-radius circle
Light output	10,000 footlamberts min. (note 4)	15,000 foot lamberts (note 4)
Accelerator current	2000 μa at 10,000 fL	1100 μa at 15,000 fL
Useful scan diameter	4 3/4 inches	4 3/4 inches
Max. outside diameter	5.428 inches	5.425 inches
Overall length	21 inches, max.	17 31/32 inches

TABLE IV (Cont.)

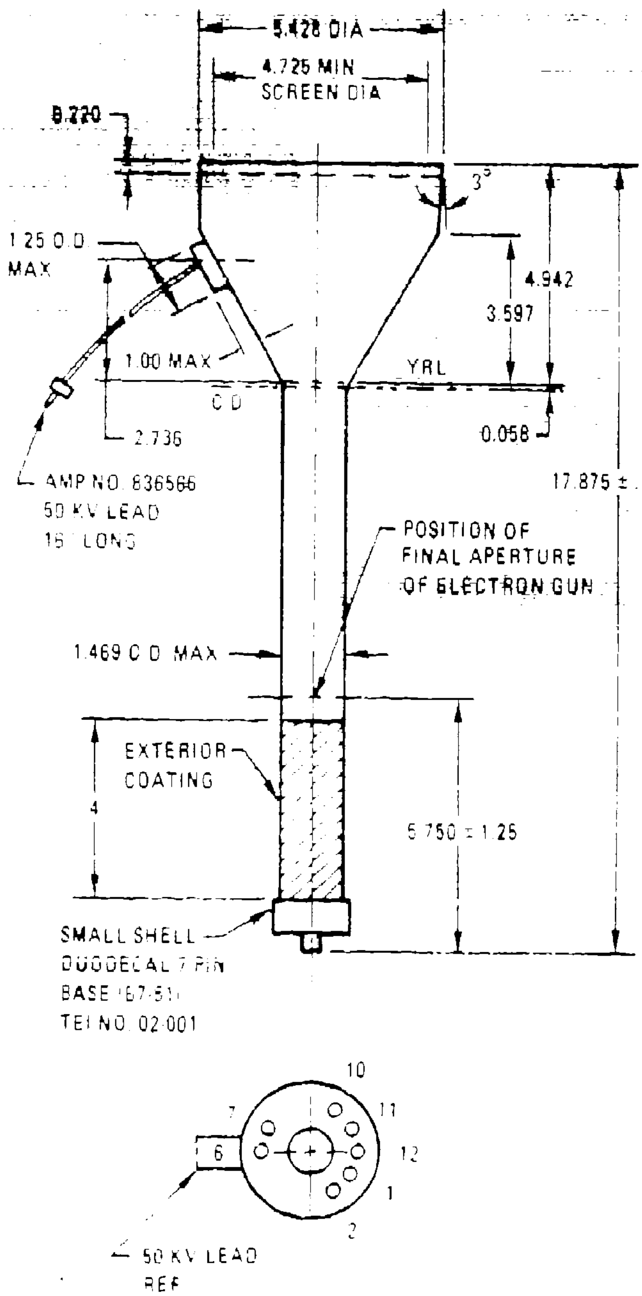
PARAMETER	SPECIFIED	TEST RESULT
Phosphor Luminances		
Red	1500 fL ± 10%	1720 fL
Green	7900 fL ± 10%	9500 fL
Blue	600 fL ± 10%	540 fL
General Dimensions	not specified other than above	see Figure 39

Explanatory Notes for Table IV

1. Visual extinction of undeflected, focused raster.
2. Measured at minimum high light brightness output.
3. With the tube shielded against external influences, the undeflected and focused spot will fall within a 3/8"-radius circle concentric with the tube face center.
4. The area brightness is measured using a 15 minute aperture of a Pritchard Meter; 1" x 4", 264 - line raster.

The CRT as delivered, met all of the specifications except that the phosphor ratios were slightly out of tolerance. Specifically, the amount of the blue phosphor was somewhat less than we specified in relation to the red and green phosphors. The effect of this was to make the green primary more pure, but to produce a lower blue brightness. The tube did produce more total light output than was specified, however, and we elected to accept delivery from Thomas Electronics since the other parameters were satisfactory and the phosphor ratios were not sufficiently in error to prevent satisfactory operation of the CRT display.

This CRT has been installed and has been operating in the Real Time Improved Color Image Display for over 8 months. The overall performance of the display using this CRT is discussed in Section 1.



PIN NO.	ELEMENT
1	HEATER
2	GRID NO. 1
6 & 7	SPARK TRAP-GROUNDED
11	CATHODE
12	HEATER

Figure 39 5M117PX71M

4.4 AREAS FOR FURTHER INVESTIGATION

4.4.1 Cooling of the CRT

The five-inch CRT used in this investigation is composed of two types of glass. The face-plate is a proprietary barium glass, manufactured by Corning Glass Works, whereas the bell and neck are formed of common 0120 lead glass. Experimental testing of CRTs made of soft glass have shown that the average faceplate power dissipation must be held to less than 1 watt per square inch if one is to avoid cracking of the faceplate. For the three inch by three inch raster, we obtained 9 watts which translates to 225 microamperes of average beam current at 40 kV anode voltage using the highest picture duty cycles. Since the peak beam current for the 5M117 exceeds 1.6 milliamperes we see that 225 microamperes represents a duty cycle of only 225/100a=14% for the CRT. Many pictorial scenes and inverted (black-on-white) alphanumeric display formats can easily exceed this duty cycle and possibly destroy the CRT by excessive heating.

Two possible solutions to this heating problem have been employed in past designs. The first has been to aircool the faceplate, however, this is difficult to implement effectively since the space between the lens and the CRT is usually less than 1/4" for a high efficiency refractive optics display. The other approach taken has been to construct the faceplate of a more rugged material. Hard glass has been tried and will withstand higher thermal loads, but usually darkens rapidly due to x-ray induced color centers. Raytheon has taken a novel approach and has constructed a CRT with a faceplate of crystalline sapphire. The sapphire has a thermal conductivity around 38 times higher than that of glass. Thus, much higher thermal loads can be tolerated without building up destructive thermal gradients in the faceplate. Raytheon has also implemented a cooling collar around the periphery of the screen area through which a dielectric cooling fluid can be circulated. The disadvantages of the Raytheon tube are the high cost of approximately $5,000 (in unit quantities) and the existence of "twining" defects in the crystalline sapphire which result in different optical properties in the sapphire along different directions. The end result of these defects is a loss of optical resolution in the area of the "twining" defect. Conversations with Raytheon have revealed that it is practically impossible to obtain sapphire entirely free from "twining".

In summary, some improvement in power capability can be expected if air cooling is used. Large improvements in power capability result if a sapphire faceplate is used, but the extent of the resolution loss due to "twining" would have to be studied to reach a conclusion about the suitability of this approach for high resolution projection applications.

4.4.2 Resolution (line width) Improvements

At the present date, 3 mils is about the best line width (shrinking raster) that has been obtained for high brightness projection CRTs. This is mainly due to the large cathode areas and aperture sizes needed in the electron gun to achieve high beam current densities.

It appears that the best way to guarantee good modulation at 1000 TV lines for a refractive projection system will be to use larger CRTs and lenses and employ precision linear amplifier type focus correction. Some benefit might be obtained by anti-astigmatism correction using two axis cylindrical field corrections both static and dynamic. These elaborate dynamic spot size correction systems are usually only found on precision display systems utilizing spot sizes less than 1 mil; however, some improvement would be realized if these correction methods were used on CRTs such as the 5M117.

The resolution can also be improved by utilizing better deflection yokes. There are many tradeoffs in the design of uniform precision deflection yokes and Philco-Ford's experience has been that the yoke selection must be done empirically. Since, a yoke which performs well on one CRT type may not perform well on a different CRT. The present yoke is a Celco FYS448, which is a special high sensitivity, low inductance yoke designed for use with a projection CRT identical to the 5M117 in physical characteristics. A shorter yoke would require increased deflection currents but at the same time would decrease the spot astigmatism caused by the longer yoke. At the high deflection speeds required by this display, it may not be possible to increase the deflection current appreciably because of current and speed limitations in present semiconductors. Further detailed study of high speed magnetic deflection systems is currently progressing at Philco-Ford to evaluate new yokes and new circuit designs.

SECTION 5

OPTICS CONFIGURATION

5.1 LENS

The lens, as initially proposed, was one which would be a refractive optic 5.3-inch focal length with a relative aperture of 1.0. The lens was to be corrected for the full spectral range of the system and the modulation transfer function maximized for the 1000-line format. Distortion in the lens was to be less than 2%. Axial transmission was to be 75% minimum.

The design and fabrication of the lens became the most complex development of the color display system.

The original specification for the procurement of the projection lens is shown in Figure 40. A lens with these performance characteristics was exceptionally difficult to design and manufacture.

The refractive lens types considered for this application were the Petzval, the Sonnar, and the double Gauss. All three lens types are capable of high speed but have considerable differences in field coverage.

The Petzval lens can cover a field up to 20° and has the advantage of shallow curves and simple construction. Its size is relatively large.

The Sonnar, smallest of the three, covers a field of about 30°. The weakness of the Sonnar is color correction.

The double Gauss is the only choice to cover a field beyond 30°. It is a complex lens with steep curves. Its color correction is very good. No difference is noticeable in its performance over the spectral range. Its only weak point is its oblique spherical aberration which is very difficult to correct.

CRT PROJECTION LENS SPECIFICATION

The lens is intended for projection, the object plane is the CRT phosphor, and the image plane a rear projection screen.

1. Spectral coverage: 3 color phosphor energy distribution:

   6% at 470 nm

   79% at 540 nm

   15% at 620 nm
2. Object: 80 mm x 80 mm
3. Image: 356 mm x 356 mm
4. Resolution: 13 lines/mm minimum at object plane both sagittal and tangental at all zones. Modulation transfer function minimum 0.50 at all zones at 0-13 lines/mm both sagittal and tangental.
5. Track length: 950 mm ±50 mm
6. Aperture: f# = 1.0 maximum
7. Field: Both object and image fields are flat.
8. Distortion: 1% maximum pincushion or 5% maximum barrel. Barrel distortion preferred to pincushion if any distortion exists.
9. Axial transmission: 80% minimum
10. Relative illumination: 70% minimum
11. Special features:
    a. Object is a CRT faceplate 5.5 ±0.5 mm thick
    b. Between the CRT faceplate and lens there will be a glass plate 6.5 mm ±0.5 mm thick (Plate glass).
    c. The minimum space between the rear of the lens mount and the front of the CRT is 10 mm.
12. Quantity: One only
13. Delivery: 90 - 120 days ARO

Figure 40 CRT Projection Lens Specification

The first two designers to work on the design failed completely. Every opportunity was afforded the vendors to suggest changes in the specification which would assist in the design but not seriously degrade performance. None were suggested. Diffraction Optics was the vendor who successfully designed the lens. They requested that the resolution specification be applied over an 80mm object dia. circle rather than an 80mm square; the relative illumination specification to apply at the edge rather than the corner. Axial transmission was to be reduced to 70%, and the color wheel moved from behind the lens to between the field flattening element of the lens and the remaining elements. The changes were acceptable to Philco-Ford, the design completed, and the lens fabricated. A photograph of the lens is shown in Figure 41. The lens system consists of 11 elements plus the color wheel and the CRT faceplace, both of which are included in the design and are required for proper performance of the lens. Figure 42 shows a cross section of the lens. The central air space was made adjustable to permit optimization of field curvature and astigmatism at assembly.

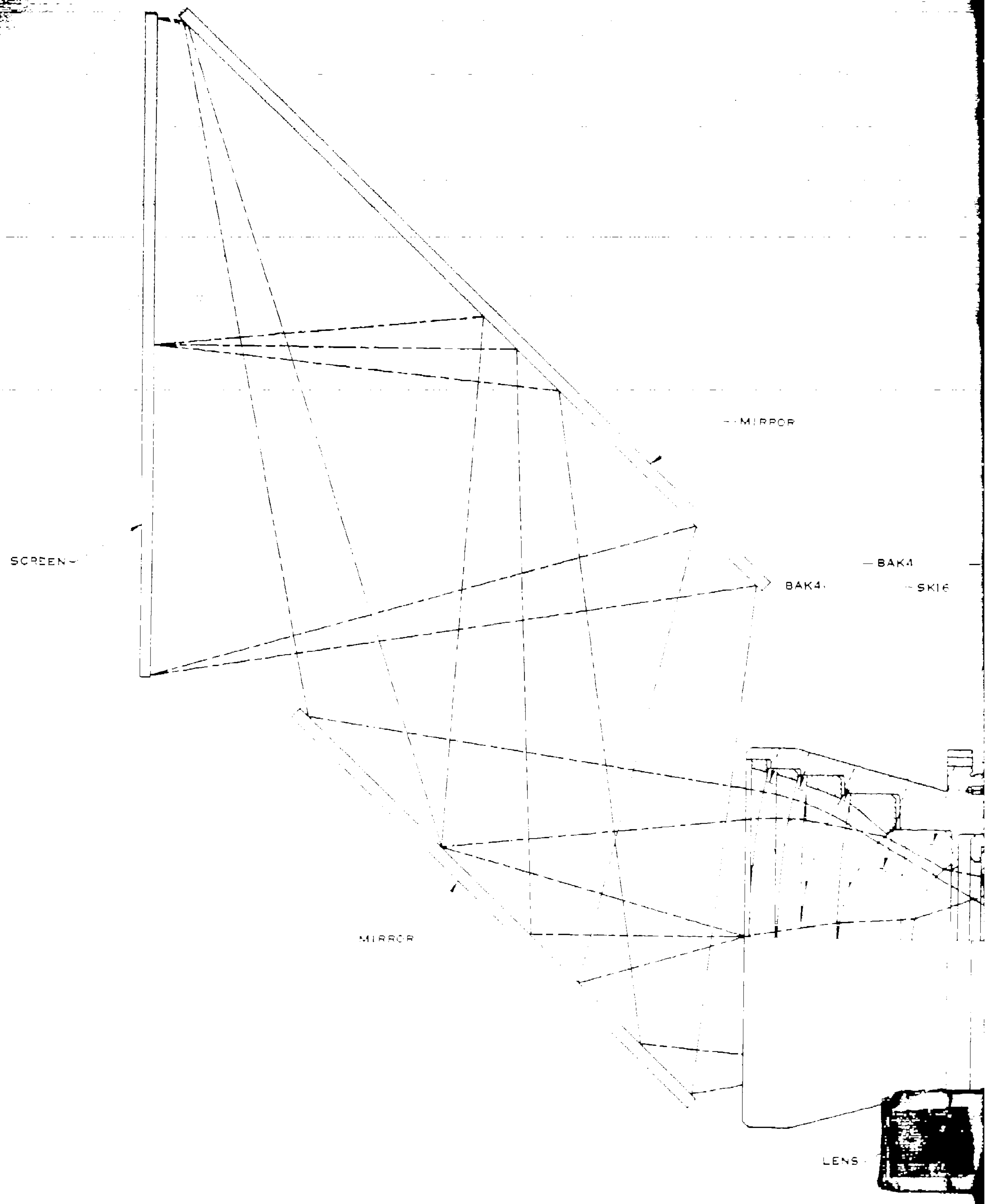
At high speed, the maximum field coverage of the double Gauss design is 40°, just sufficient for this application. Astigmatism and field curvature are well controlled, resulting in a very even performance over the field. This can be seen from the measured resolution data. Isolated areas of poor performance are not present. The use of a field flattener was found necessary in order to allow the radii of the lens element surfaces near the central aperture stop to be increased thus reducing the powers of those surfaces which are the main contributors to oblique spherical abberation. In this way, the oblique spherical aberration was kept within acceptable limits.

The glasses are of medium refractive index. Although an increase of index is, in general, helpful to the correction, a significant increase from the present level would sharply increase the cost of the glass.

The glass-types are shown in Figure 42 . Figure 43 shows the catalog design for the lens. As usual, slight deviations from the design exist in the lens because of glass variations and manufacturing tolerances. The performance is not degraded by these small variations.

Every effort was made to keep the diameters of the lens elements at a minimum and still meet the performance requirements. Small diameters make the lens lighter, easier to fabricate and, most important, allow for selection of readily available glass blanks from which the elements are made.

Figure 41 Photograph of the Lens



MIRROR
SCREEN
BAK4
BAK4
SK16
MIRROR
LENS

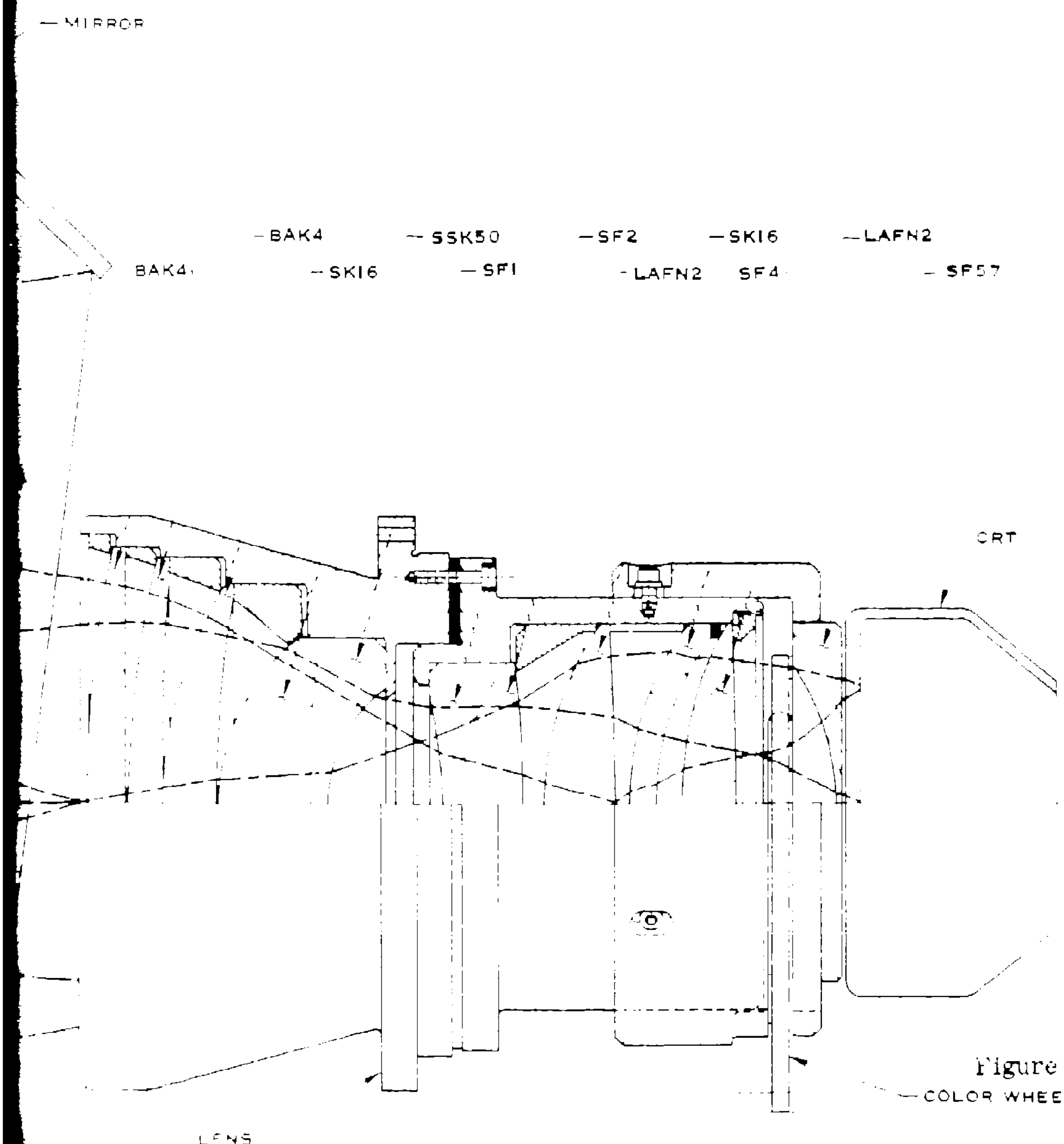


Figure 42 Cross Section of the Lens

BASIC LENS DATA*

SURFACE	RADIUS	AXIAL THICKNESS	MEDIUM	REFRACTIVE INDEX	CLEAR APERTURE
0	0.0	32.858436	AIR		
1	0.0	-8.113277	AIR		
2	16.632772	0.551181	SCHOTT BAK4	1.571243	6.80
3	511.636487	0.039370	AIR		6.70
4	13.931551	0.472441	SCHOTT BAK4	1.571243	6.40
5	47.274949	0.039370	AIR		6.30
6	5.574327	0.748032	SCHOTT SK16	1.622863	5.65
7	16.483239	0.039370	AIR		5.50
8	2.910849	1.276982	SCHOTT SSK50	1.620749	4.30
9	23.086616	0.236220	SCHOTT SF1	1.723103	3.80
10	1.975863	0.826902	AIR		2.95
11	0.0	0.787402	AIR		2.90
12	-6.404811	0.236220	SCHOTT SF2	1.652216	2.80
13	3.262086	0.874825	SCHOTT LAFN2	1.747949	3.40
14	-18.311700	0.316949	AIR		3.60
15	4.310181	0.944882	SCHOTT SK16	1.622863	4.70
16	-72.637354	0.200200	AIR		4.70
17	4.122453	0.393701	SCHOTT SF4	1.761664	4.60
18	3.877805	0.354331	AIR		4.40
19	5.541808	0.669291	SCHOTT LAFN2	1.747949	4.30
20	-71.256963	0.537273	AIR		4.30
21	0.0	0.255906	PYREX	1.480630	3.90
22	0.0	0.590551	AIR		3.90
23	-3.423076	0.078740	SCHOTT SF57	1.855035	3.70
24	0.0	0.039370	AIR		4.10
25	0.0	0.216757	TBFC	1.515100	4.40
26	0.0	0.0	AIR		4.40

EFL	BACK FOCUS	WORKING F-NUMBER	LENGTH	OBJECT-TO-IMAGE DISTANCE	MAGNIFICATION
7.2071	0.2168	1.22	10.5095	37.4664	-0.2247

Figure 43 Final Catalog Design -4.45X F 1.0 Transfer Lens for 80x80 mm Field

*All dimensions are in inches

5.1.1 Lens Evaluation

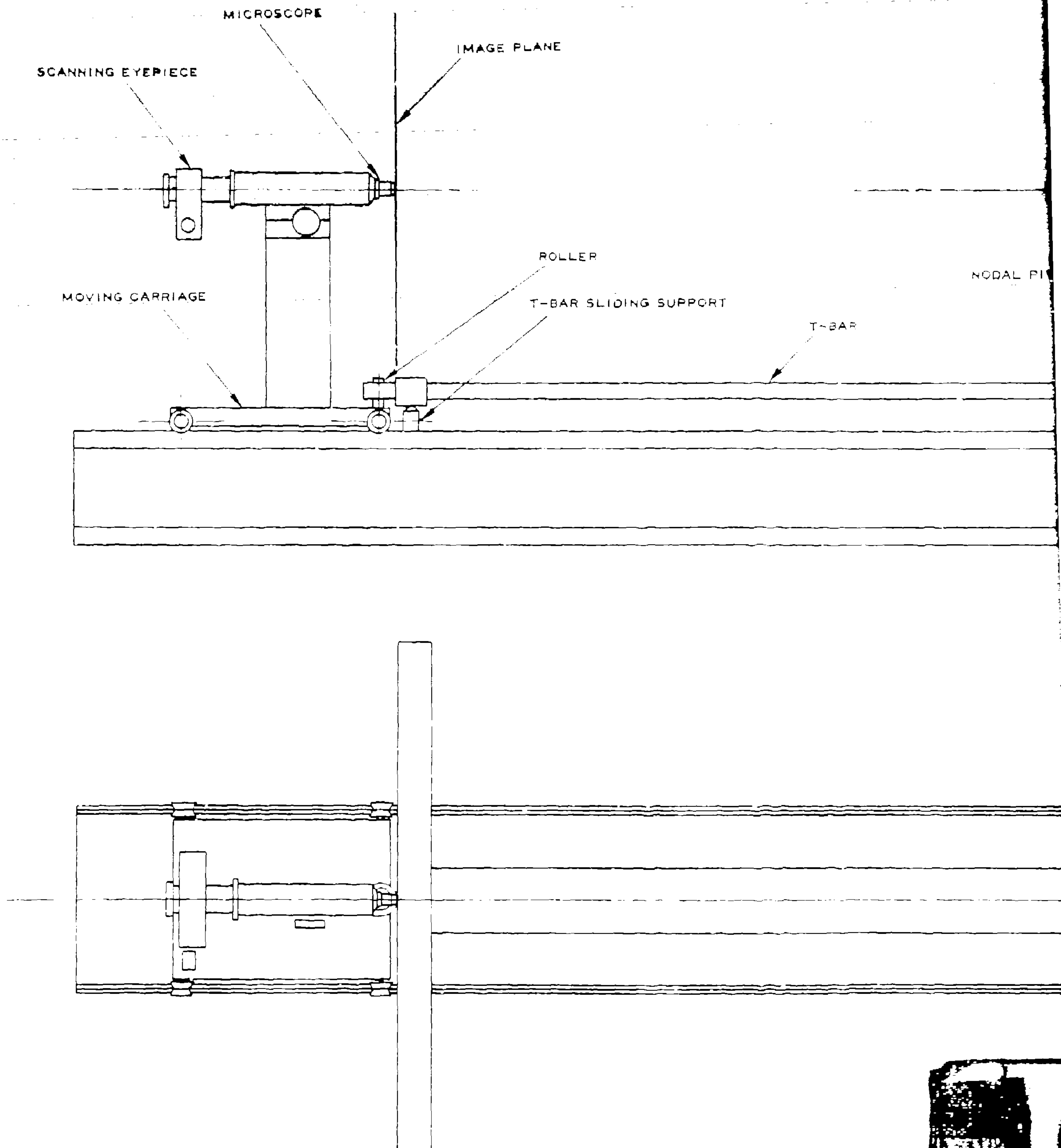
The lens was set up on an optical bench with the color wheel and glass, simulating the CRT face plate properly placed at the rear of the lens. A high contrast USAF 1951 test target was fixed on the back of the CRT faceplate. The target was backed with a ground glass placed sufficiently behind the target so that the grain at the glass would be out of focus at the projected image plane. The ground glass was used to simulate the lambertian radiation pattern of the CRT phosphor. The ground glass was illuminated by a tungsten source running somewhat over voltage to boost its output and color temperature.

The lens was mounted on a pivot located near the front nodal point of the lens. A T-bar was extended forward from the pivot point to the projected image plane and rotated with the lens. The cross bar on the T-bar defined the plane of the projected image. A detector head was set up on the optical bench and, by means of a roller mechanism, made to travel along the bench in contact with the crossbar while the lens was pivoted. In this way, the lens could be tested over its entire field. Figure 44 shows the test set up arrangement.

The detector head was an optical fiber of 50-microns diameter mounted in a micrometer to allow linear movement over some distance. The optical fiber was coupled to a photometer from which the output was recorded on a chart recorder. The depth of modulation testing was accomplished by selecting an appropriate target section and projecting it on the detector head located at the image plane. The optical fiber was made to scan across the image and the output recorded along with a reference zero level. This measurement was performed on axis, off axis at 2 corners of the designed image area, in both sagital and tangential planes and with red, green and blue filter sections in place

The target section used was group 2 part 6 of the USAF 1951 test target which corresponds to 7.2 line pairs/mm. This is in excess of the 6.5 line pairs/mm required. Figure 45 is a typical chart produced during the tests. The depth of modulation is defined as the ratio of the difference between the maximum response and the minimum response to the maximum response.

$$\text{Depth of modulation} = \frac{\text{max-min}}{\text{max}}$$



MICROSCOPE
IMAGE PLANE
SCANNING EYEPIECE
ROLLER
NODAL PI
MOVING CARRIAGE
T-BAR SLIDING SUPPORT
T-BAR

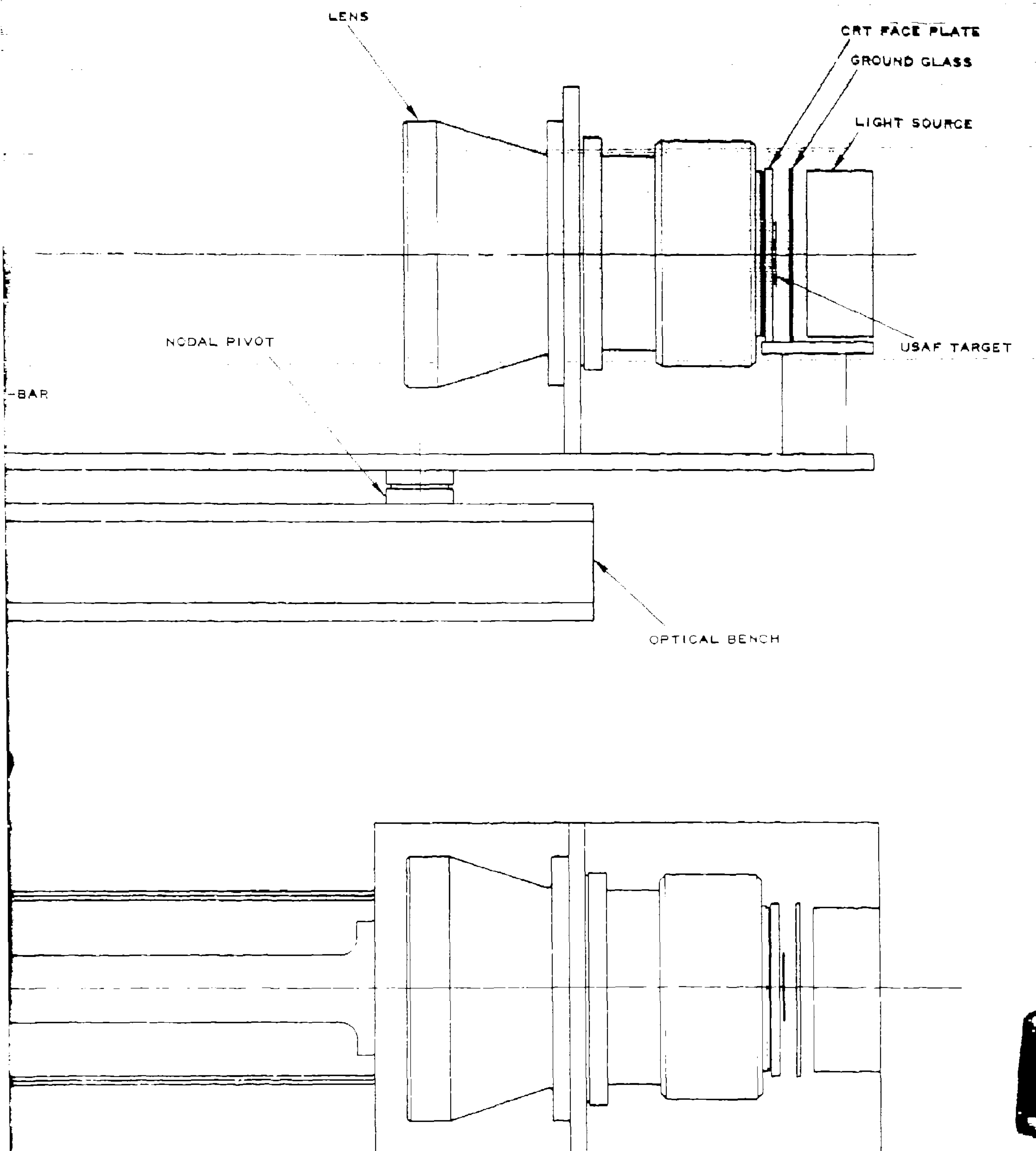


Figure 44 Arrangement of Test Setup

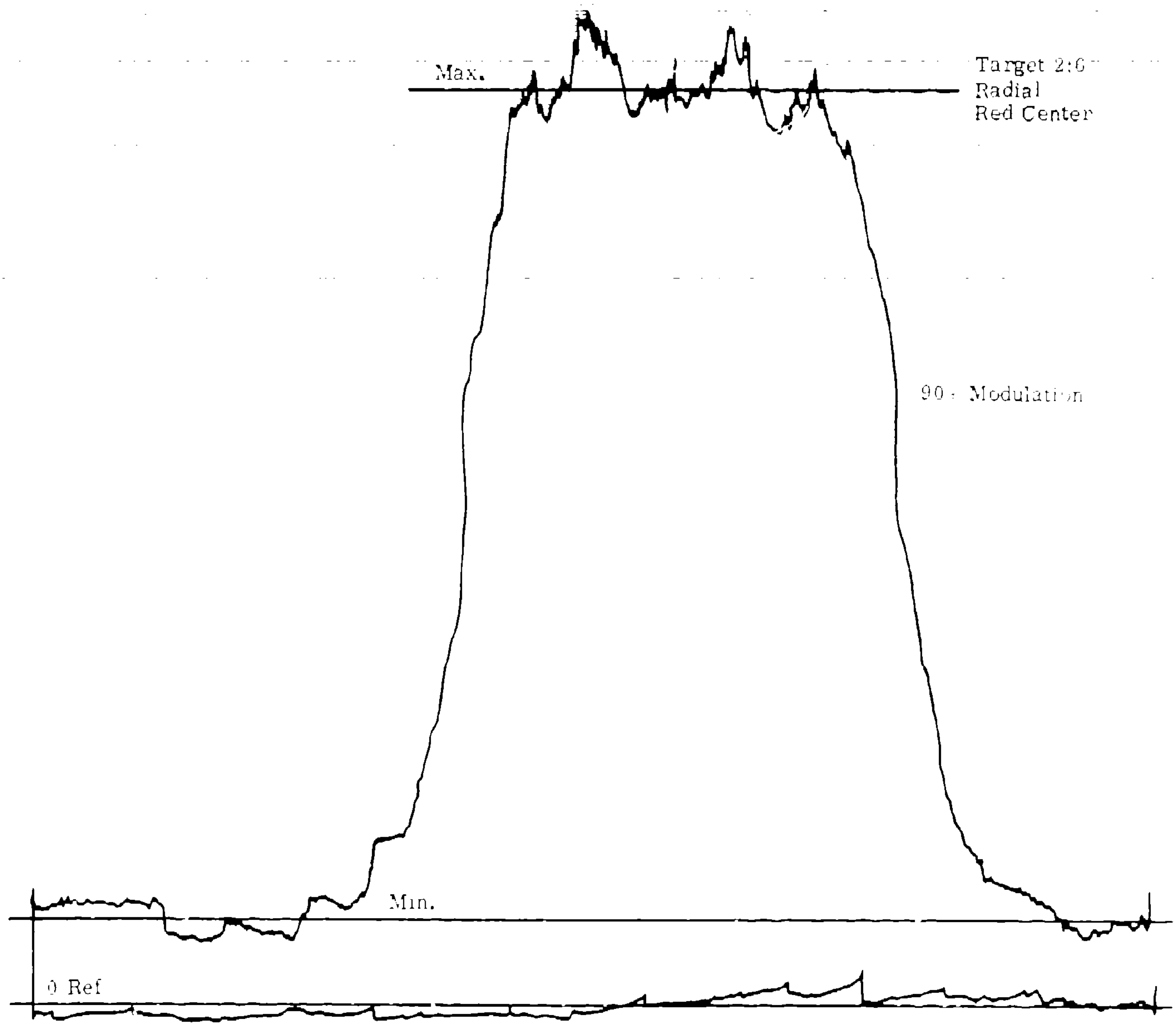


Figure 45 Typical Modulation Measurement

The axial transmission was tested by passing a collimated beam of light through the center of the lens, collecting it in an integrating sphere, and measuring all the light emerging from the lens. The measurement was then made without the lens in place. The ratio of the light measured with the lens to the light without the lens is the axial transmission.

The relative illumination was determined by use of an extension of the axial transmission test. The test setup and procedure was identical to that used for the axial transmission measurement except that the transmission was measured at two off-axis positions, the edge of the field, and the corner of the field. The relative illumination is the ratio of the off-axis transmission to the axial transmission.

The field flatness measurement is implicit in the depth of modulation measurement. The aperture and distortion are determined in the design of the lens and were not measured.

<u>Performance Results</u>

1. Depth of modulation:	0.85 to 0.93
2. Axial transmission:	76%
3. Relative Illumination:	edge 0.83
	corner 0.50

Complete data is contained in Appendix V.

Figure 42 also shows the ray trace through the complete optical system from the phosphor to the viewing screen.

The particular optical configuration, shown in Figure 42, was chosen to permit the display to be packaged with as little wasted space as possible. The only real degree of freedom is in the folding of the light rays after leaving the lens.

The material used for the viewing surface was a diffuse plastic screen made by Pola Coat. This is a fine-grain material with a resolution on the order of 40 line pairs/mm; far in excess of the 4 line pairs/mm to be displayed. The material is available in various gain values. Selection of the screen gain will influence the image brightness and viewing angle of the display. The light hitting the screen is redistributed into a radiation pattern dependent on the gain. A high-gain screen causes most of the light to be beamed forward in a narrow cone so that a viewer on axis sees a bright image while a viewer off axis sees a dim image. A

low-gain screen tends to make the radiation pattern very broad so that no matter where a viewer is located, the image viewed will have the same brightness. The maximum brightness observed with a high-gain screen will be more than that with a low-gain screen assuming the same source radiation.

The lens designed for this application exhibits exceptional performance in all parameters and, at the same time, is rather compact compared with other lenses of similar but poorer performance obtained for earlier applications. To achieve the 0.85 depth of modulation factor over the entire field in an f/1.0 lens is even more significant when the flatness of both the image and object planes is considered along with the 32° full-field angle. Perhaps the only disappointing area of performance was an axial transmission of 76%, but disappointing only in comparison with the excellent performance in the other areas.

Lens Performance Summary

1. Object size	80 x 80 mm
2. Image size	356 x 356 mm
3. Track length	950 mm
4. Relative aperture	1.0
5. Depth of modulation at 6.5 line pairs/mm	0.85
6. Axial transmission	76%
7. Relative illumination	83% edge, 50% corner
8. Distortion	-1.2%

Physical Parameters:

1. Length	11.0 inches
2. Diameter	8.0 inches
3. Weight	33 lbs

The present design represents the state-of-the-art in high-speed wide-angle projection lenses and its complexity has reached a practical limit. Resolution could be traded however, with speed. If a reduction in resolution could be tolerated, an increase in speed could be obtained. For instance, a depth of modulation of 0.6 could be obtained at f/0.8 and 6.5 line pairs/mm. similarly, a reduction in speed would allow greater resolution. Field coverage seems to have reached its upper limit.

5.2 COLOR WHEEL DESIGN CONSIDERATIONS

The color wheel as initially proposed was to be a new development. The wheel was to consist of a glass disk 12 inches in diameter and 0.125 inches thick. The wheel was to have evaporated on to it multilayer filters of appropriate spectral peaks and bandwidths. These filters would form a ring 4 inches wide around the periphery of the wheel. The wheel was to be mounted between the CRT and the rear of the lens so that the filter section would cover the active area of the CRT faceplate: an area 3.1 inches x 3.1 inches. The filter sections would be shaped to assure proper registration between the advancing raster and the rotating interface between different color sections on the wheel. Using the design ground rules, as stated above, the following parameters were considerations in the mechanical design of the color wheel.

1. Size and shape of the color sections
2. Overall wheel size
3. Method of manufacture
4. Mounting method
5. Mechanical mounting and drive.

The primary requirement of a color section is that it follow the vertical travel of the raster. That is, whenever the field representing a particular color is being generated, a filter of that particular color must, at all times, overlay the spot generating the field. Also, since the phosphor has some finite decay time, it is important that only the desired color filter overlays any particular spot until the phosphor has decayed below visibility. Alternately, an opaque section of the wheel may cover the decaying phosphor. However, the opaque section is undesirable because it prevents potentially useful light from passing through the wheel.

The size and shape of the filter sections are determined primarily by the size of the raster and the position of the center of rotation of the wheel. These parameters also determine the minimum overall diameter of the wheel.

The 6-inch diameter of the CRT mount and the anticipated large rear diameter of the projection lens dictated that the center of rotation of the color wheel be approximately 4 inches from the center of the CRT faceplate. In order to minimize the overall diameter of the wheel, the center of the wheel was located as shown in Figure 46.

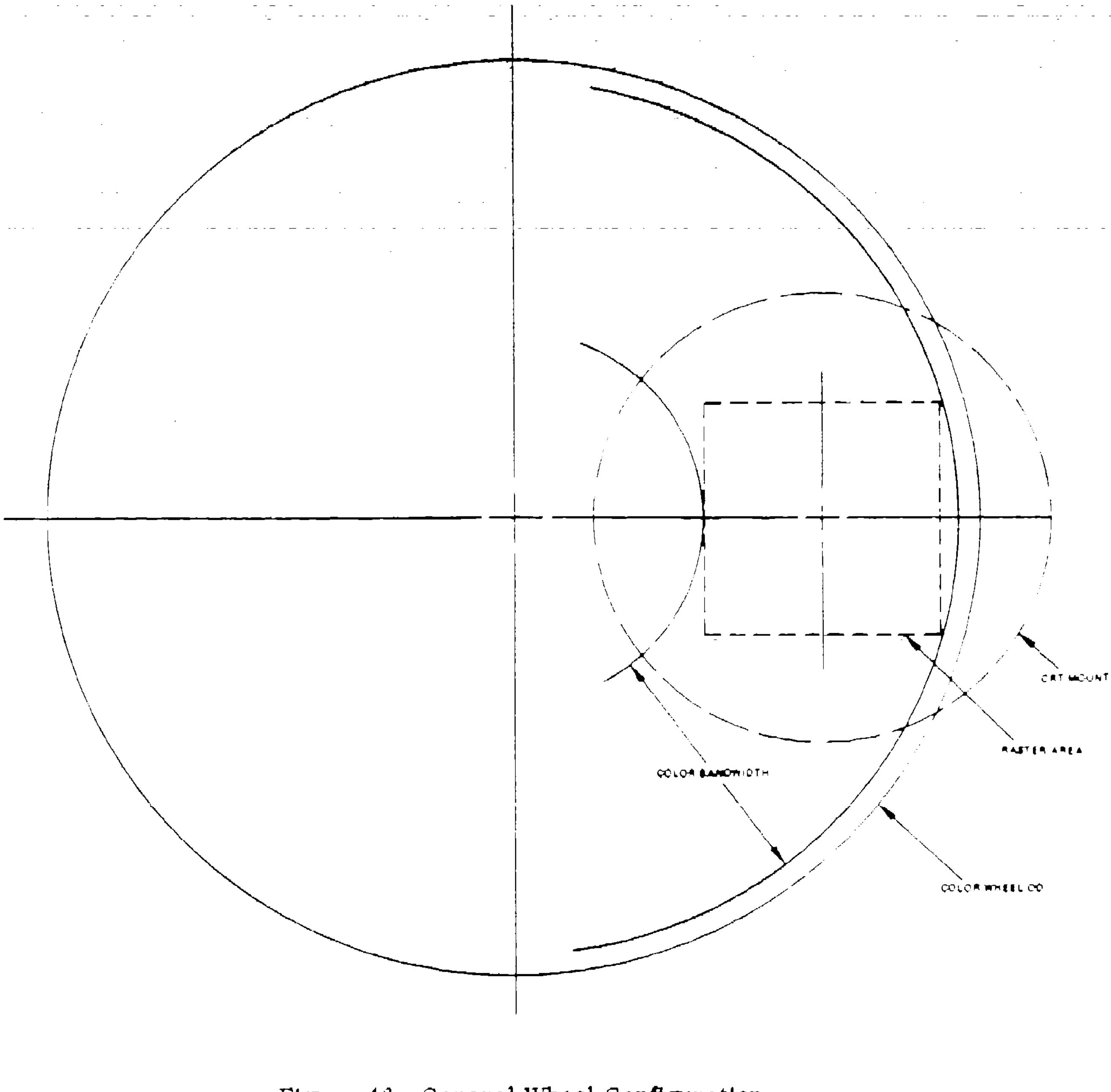


Figure 46 General Wheel Configuration

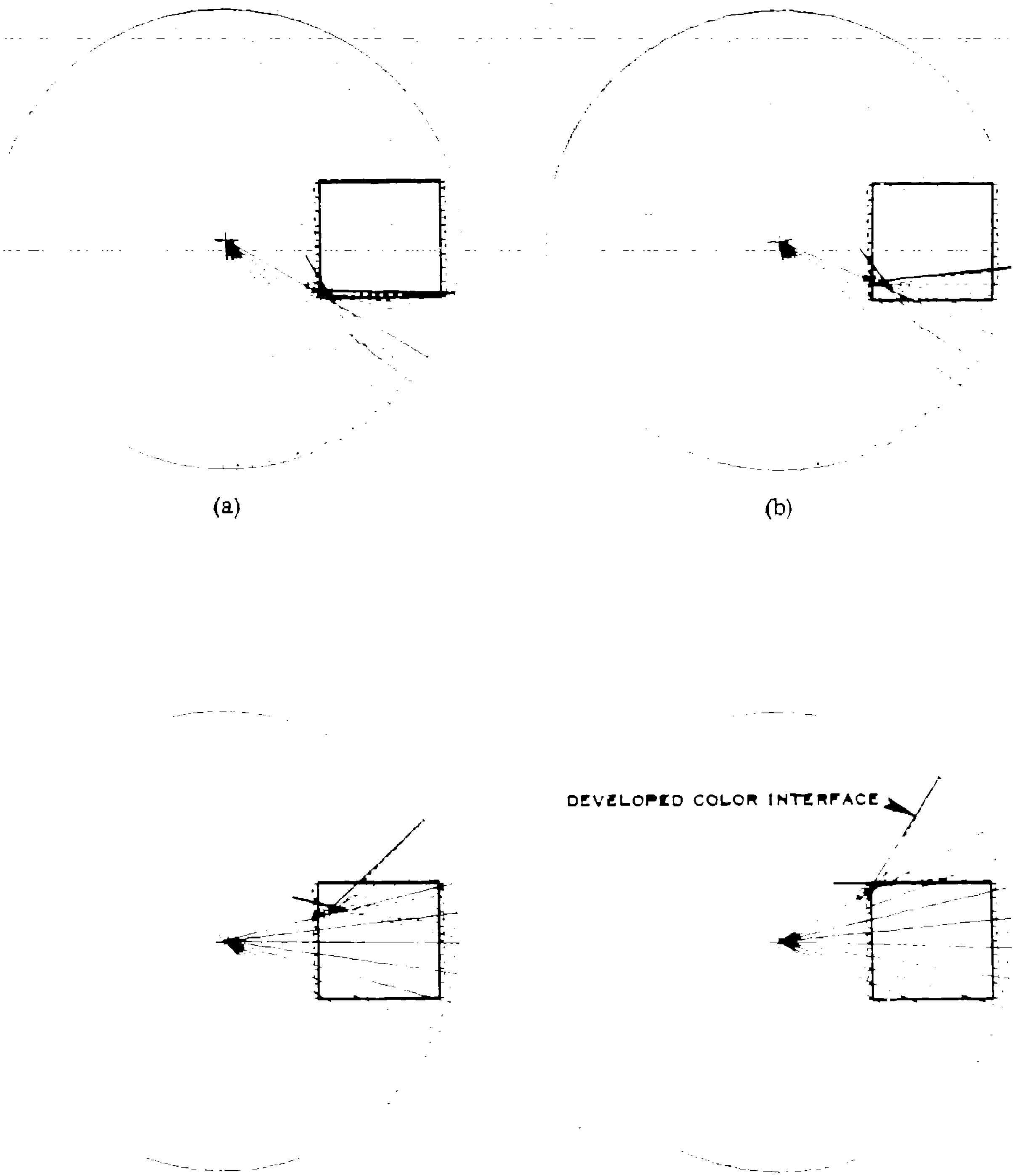
The choice of center location resulted in an overall filter diameter of 12 inches. The width of the filter band on the wheel was determined by swinging two arcs concentric with the center of rotation which contained between them the entire scanned area on the CRT faceplate.

To minimize the rotational speed of the wheel, the number of color sections was maximized. It was considered desirable that each filter section be able to cover the entire raster area and thereby assure maximum utilization of the light from the decaying phosphor. The maximum number of sections possible to meet this parameter is 6; 2 red, 2 green, and 2 blue, the number of sections must, of course, be an integral multiple of 3.

The next requirement was to determine the shape of the filter sections so that as the wheel rotated and the raster advanced, the proper color would always overlay the raster. This was determined graphically in the following manner. A paper disk was cut approximately 13 inches in diameter to simulate the color wheel. A 3.1 inch square opening was cut in another piece of paper to simulate the scanned area on the face plate of the CRT. A 60° section of the paper disk was divided into 8 smaller equal sections which were numbered in a clockwise direction. Vertical edges of the square cut out were marked off into 8 equal sections which were numbered from the bottom. The disk and cut-out sheet were arranged as in Figure 48 with the cut-out sheet fixed while the disk was free to turn beneath it. The disk was rotated so that the upper edge of section 1 coincided with the lower left corner of the cut-out. The lower edge of the cut-out was then traced onto the disk (Figure 47a) and the disk rotated until the upper edge of section 2 was coincident with the lower left corner of the cut-out (Figure 47b).

A line parallel to the lower edge of the cut-out was then traced across the opening onto the disk at the lower edge of section 2 on the cut-out. This procedure was repeated for each wheel section and cut-out section (Figure 47 c, d).

The resulting family of traces is shown in Figure 47. The uppermost edge of this family of traces is the required shape of the boundary between the color sections on the wheel. The boundary was then extended to the inner and outer edges of the filter band to define the shape and size of the color sections on the wheel. Figure 48 shows the arrangement of color sections on the wheel. The wheel was designed to be slightly over-size for ease of manufacture and to provide some margin around color section.



(a) (b) (c) (d)

Figure 47 Resulting Family of Traces

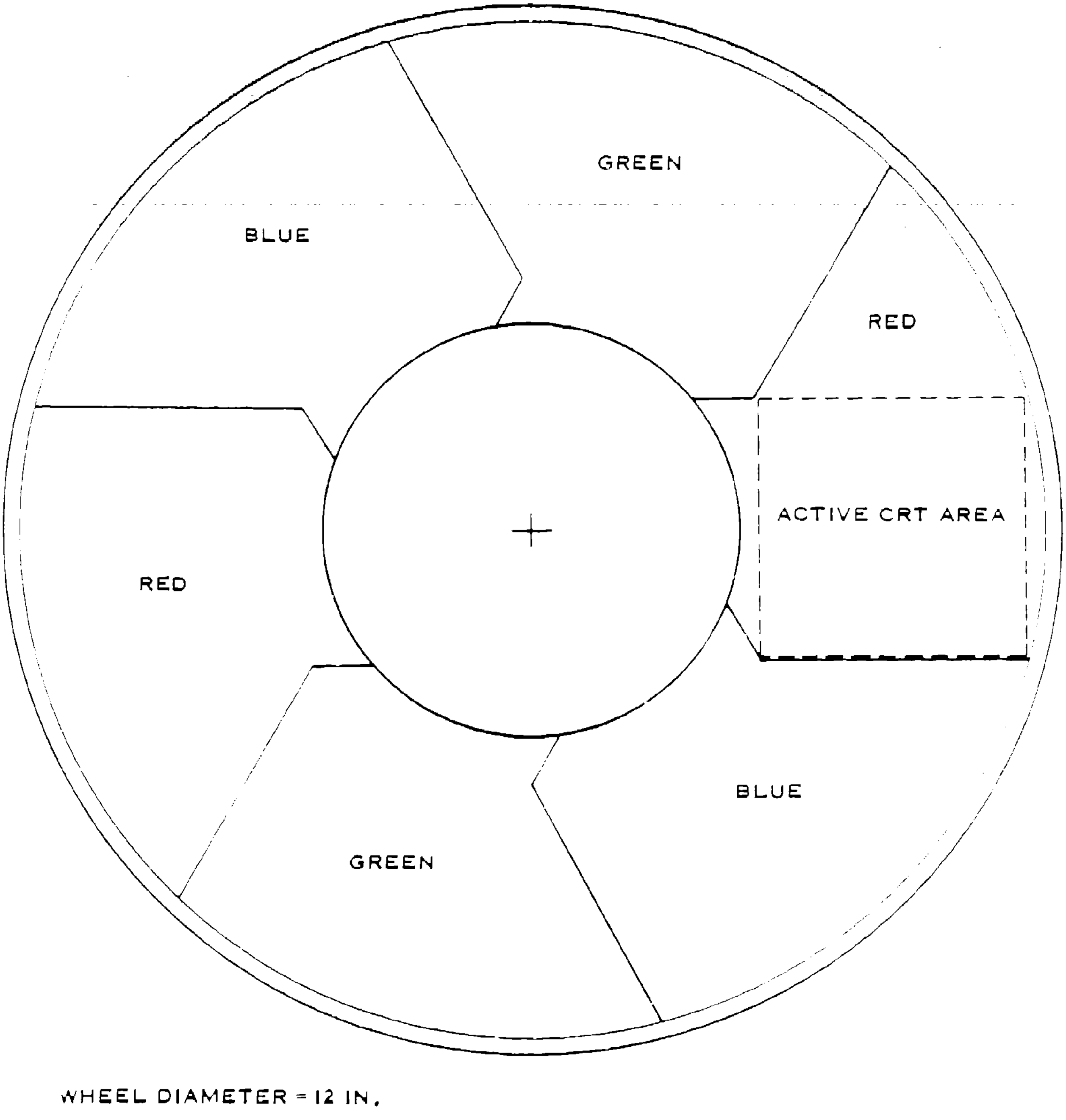


Figure 48 Arrangement of Color Sections on Wheel

Early in the program it was concluded that the usual absorption filters would be unacceptable because of their low peak transmission and shallow band edge slopes. Interference filters on the other hand have exceptionally high-peak transmissions and readily controllable band edge slopes.

It was, therefore, decided to use interference filters for the color wheel. Bausch and Lomb was selected as a vendor and an evaporation mask and substrates forwarded to them. The substrate material was plate glass, one piece of which was to have the color sections deposited on it and then be laminated to the other piece of plate glass with the filters in between the two. The outer surfaces were to have broad band anti-reflection coatings to minimize the scattering of light in the completed system.

5.2.1 Design Implementation

The first attempts to deposit the filter sections resulted in broken substrates. The vendor concluded that thermal stresses were responsible and changed the substrate material from plate glass to pyrex. The pyrex was chosen with considerable care to obtain material without the gross optical defects common to pyrex. Examination under a polariscope showed no visible defects in the area to be used for the filters. Two wheels were delivered, the first was rejected because of unsatisfactorily placed peak transmission in the red section and excessive blue transmission in the red section. The excessive blue was a result of the peak transmission in the red being displaced to the longer wave lengths. The second wheel was found to be acceptable although its thickness increased 0.005 inch across the diameter which made balancing somewhat of a problem.

The wheel was supplied with a 1 1 4-inch center hole into which an aluminum hub was bonded to mount the wheel to the drive shaft. The wedge required that the wheel be offset on the hub to achieve balance. The amount of offset was experimentally determined and the wheel was bonded to the hub. The lens designer confirmed that the wedge would not degrade the image quality of the system to any visible extent.

The wheel is driven through a set of crossed nylon helical gears by a servo controlled motor.

5.2.2 Performance Evaluation

The wheel was tested for accuracy of peak transmission placement and magnitude of peak transmission by Bausch and Lomb. Figure 49 shows the results of their tests. Comparison of the spectral transmission curves of Figure 49 with the spectral curves of the phosphors (Figures 22, 23, 24) show the phosphors to be located well within the color band, with the exception of the blue phosphor which is exceptionally broad banded. The color bands are much broader than the red or green phosphors. This is necessary since the transmission band of the filters moves toward the shorter wavelengths when used off-axis. The light from the phosphor is essentially lambertian and therefore passes through the filters over a very wide angle. The lens passes the light through the color wheel at angles up to 25° off axis. The filter band must be broad enough so that even when the band has shifted by the amount caused by the light being 25° off axis, the phosphor wavelength is still in the filter pass band. The amount of shift toward the blue end of the spectrum is dependent on the width of the band pass in a band pass filter and the sharpness of the cut off on cut off filters. In the color wheel, the red and blue filters are cut off filters and the green is a bandpass filter. Light at 25° off axis to the green filter causes a shift of about 16 nm towards the blue. The shift in the blue is about 15 nm and the red is about 18 nm. In all cases, the phosphor peak is still in the maximum transmission portion of the filter. Also, the lower edge of the red filter does not pick up the green phosphor. Because of the broad spectrum of the blue phosphor, the green filter does pick up some energy from it. This pickup tends to reduce the purity somewhat. In summary, the color wheel has filter sections designed to make use of all the available light from the phosphor decay period. The colors have been chosen to obtain the highest purity possible with the phosphors being used and the type of filter selected to maximize the transmission at the appropriate wavelengths.

A photograph of the color wheel, shown in Figure 4, does not present the colors of the filter sections accurately, because of the angle from which the photos were taken and the inaccuracies in the printing process used to reproduce the photo.

In terms of the color wheel, there is little that can be done to improve the display image quality.


100
90
80
70
60
50
40
30
20
10
0
PERCENT TRANSMITTANCE
BLUE
GREEN
RED
GREE
400
500
550
Nanometers

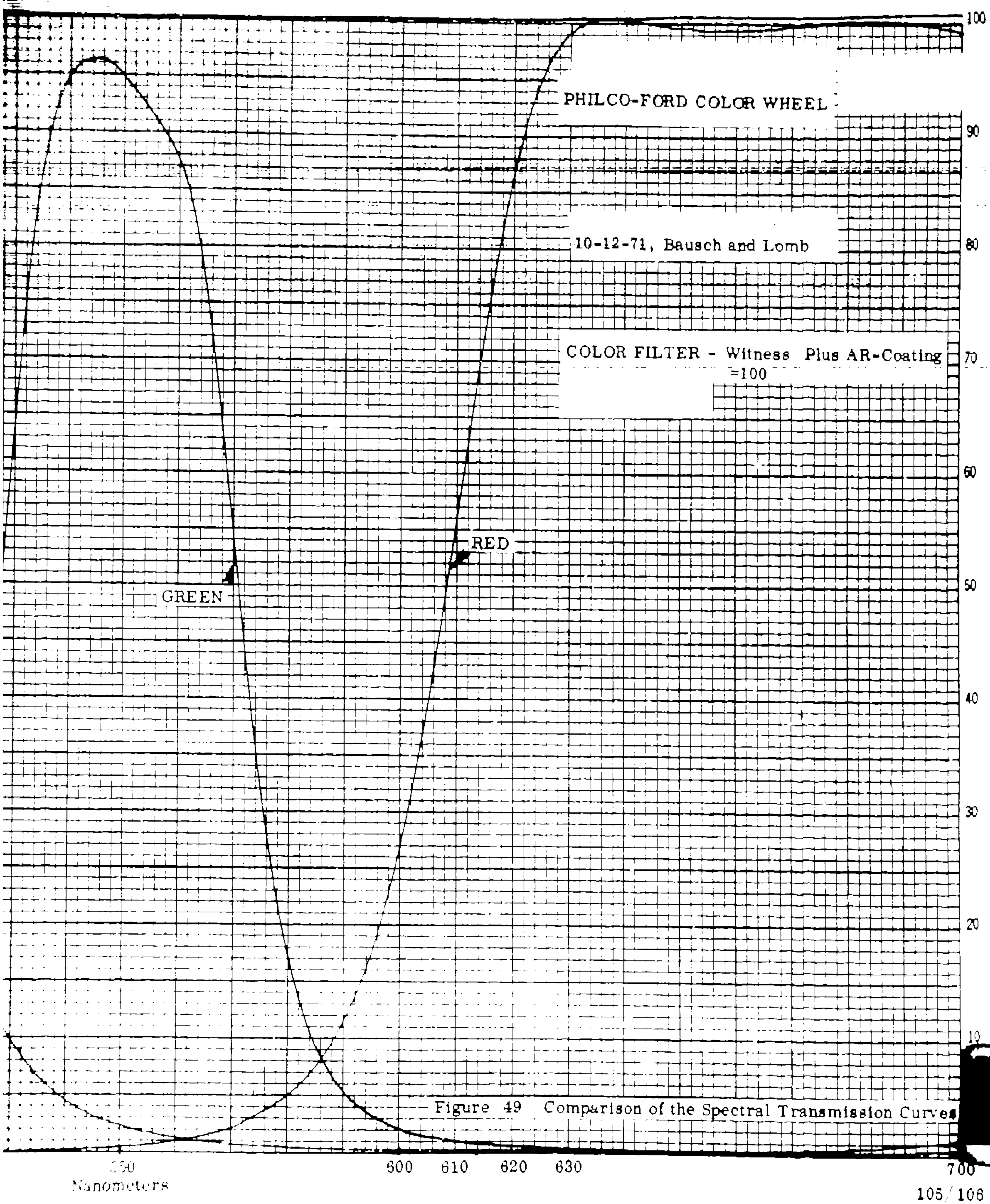


Figure 49 Comparison of the Spectral Transmission Curves

5.8 Mechanical Packaging

Circuits. Most circuits are mounted on etched cards; the very high frequency pattern generation cards use an etched card for the mounting of components and distribution of power while signal wiring is done with discreet point to point wiring. The high-power circuits such as the horizontal deflection circuits are mounted on heat sinks with the wiring done point-to-point.

The low power cards and the pattern generation cards are mounted in a card cage with wire wrap interconnects. The video amplifier is mounted as close as possible to the CRT socket.

CRT Mount. The mount used for the CRT is one developed to allow the tube to be used in environments of extreme shock but still be available for ease of replacement. The mount not only holds the CRT but also holds and maintains alignment of the focus coil and deflection yokes. It precisely locates the face place of the CRT so that the interface with the projection lens is accurately maintained.

Enclosure. The enclosure is designed so that the sides and back fold out flat to permit ready access to all electronic and mechanical parts while permitting fairly dense packing when in the normal operating configuration.

Front Panel. The front panel (Figure 50) contains the viewing screen and operating controls. The front panel area represents the minimum area for the display assembly.

The control panel has been carefully designed to permit and effective man machine interface.

Optical Subassembly. The optical components including the CRT have been brought together in a subassembly which locates all of the components independently of any other structures or components. The subassembly is designed to be rigid to maintain proper optical alignment.

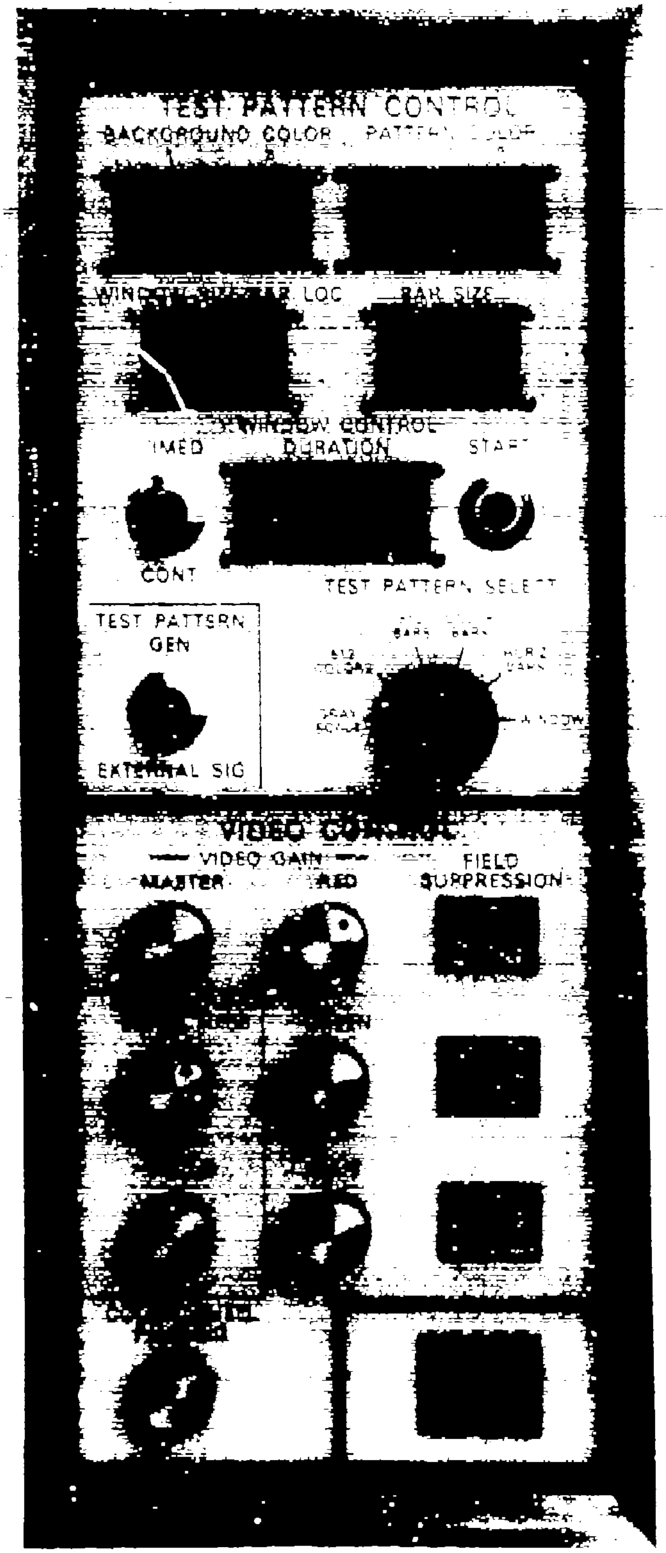


Figure 50 Photograph of Front Panel

Recommended Packaging Method for Airborne Application

The only area which would present any special problems for airborne use is the optical assembly. Mounting the screen, folding mirrors, lens and CRT would be done with a rigid space frame to make a single module.

The color wheel and its drive would have to be designed so that they could withstand the forces exerted on them as a result of the high rotational intertia of the wheel and the movement of the aircraft. This design would be straight-forward and involve strengthening of the rotating components.

With the exception of the special precautions to be taken with regard to the high accelerating voltage on the CRT, the electronics would be packaged using existing airborne packaging methods.

Weight Reduction

There are two areas where significant weight reductions may be made.

1. Power Supplies: By changing the low voltage power supplies from ground based equipment types to airborne types and eliminating the power supply for the test generator, 24 lbs can be removed from the display.

2. Physical Structure: By designing the mechanical structure of the display to include lightening holes and incorporating other weight reducing structural changes, approximately 60 lbs out of 110 lbs of structure can be eliminated. By fabricating the structure of magnesium rather than aluminum, the weight can be reduced 77 pounds. The change to magnesium would result in an approximate 100% raw material cost increase and a 15% fabrication cost increase.

The total weight reduction possible is then 101 lbs for a total display weight of 210 lbs.

Volume Reduction

If the display is to be packaged in a rectangular enclosure with no other systems or portions thereof included in the enclosure then a reduction of 1 cubic foot could be readily achieved.

If, however, the enclosure need not be a rectangular solid, or if other systems may be included in the space consumed by the display enclosure, then the volume actually consumed by the display could be reduced by another 1.5 cubic feet. It is, therefore, possible to package the display so as to consume only about 10 cubic feet.

SECTION 6

VIDEO SYSTEM

The development of a video amplifier was outlined as one of the primary tasks of this display development. The outstanding feature of this effort has been the successful development of a high-level, wideband video amplifier capable of driving a projection CRT.

6.1 DESIGN GOALS AND SPECIFICATIONS

In order to make the video system as versatile as possible, a variety of signal processing functions is considered. For example the display is of the sequential color type, with information presented in three different colors; the video information for the different colors is time multiplexed. That is, information is provided for a red field during a (5.5 msec) field interval. The red field is followed by a green field and then by a blue field. In order to select the desired color mixture, a circuit is required which will change the gain of the video system for successive fields.

The drive required by the CRT is an important factor in defining gain and greatly influences design of the output stage. The display timing and resolution requirements determine the minimum bandwidth requirements of the video system. Input signals may be supplied from various sources which may provide signals of different peak to peak levels. As a result, a gain control circuit is required since the contrast of the displayed image depends on the signal level driving the CRT.

The design goals and specifications are derived in three areas: Input characteristics, Output characteristics, Signal processing.

Requirement Summary. The areas of consideration in designing a video system are summarized as follows:

Input characteristics:

- Input signal
- Input characteristics of video system

Signal processing and output considerations:

- Bandwidth
- Gain/gain control
- DC restoration
- Color balance/suppression
- Shading correction
- Digital blanking
- Gamma correction
- Load characteristics
- Output characteristics of video system

6.1.1 Input Characteristics

Signal:

The input characteristics are outside the design influence of the video amplifier. These characteristics can be easily implemented in the interface circuits and would include the following restrictions:

- During the horizontal retrace period the average signal level will assume the black reference level for the scan line which follows it.

- During the scan line, the maximum white signal level will at least be one volt positive with respect to the black reference level.

- The maximum difference in average voltage in the video input during two consecutive (black references) horizontal retrace periods will be 20 mV.

- Maximum video signal plus common mode signal on input conductors will not exceed ±6 volts (with respect to video system ground).

- Signal is to be differential and operate into a 75 ohm resistive load.

In order to interface with high speed video sources, the input to the video system will be terminated in 75 ohms (resistive). This is a convenient value since it is common to many video systems and coaxial cables of 75 ohm characteristic impedance are readily available.

To insure video signal transmission, the video system will have a differential input for the rejection of common mode signals. Inputs to the system may range from +6 to -6 volts (common mode plus video signal).

6.1.2 Output Characteristics

The video system is required to drive a cathode ray tube (CRT). The CRT characteristics are those of 5M117PX7 M from Thomas Electronics selected for this display.

The resistive part of the impedance of this CRT load is on the order of the maximum beam current divided into the cut-off voltage for grid-cathode drive. Thus,

$$R_L \simeq \frac{80 \text{ volts}}{2 \text{ ma}} = 40 \text{ k}\Omega$$

The input capacitance of the cathode is not stated in the CRT specification, but measurement shows it to be on the order of 8 pf.

$$C_L \simeq 8 \text{ pf}$$

An additional characteristic of the load must be considered. There are occasional high voltage transients induced on the CRT electrodes by random arcing of the anode potential inside the CRT. This arcing presents a hazard to any circuits attached to CRT electrodes. The beam current, grid-cathode voltage characteristics require a maximum of 80 volts modulation applied to the grid-cathode circuit to obtain the adequate light output for the display.

From the above considerations, the output of the video system must be capable of driving the load described, i.e., 40 kΩ shunted by 8 pf. It must supply the load with 80 volts of modulation at the required bandwidth of 65 MHz (paragraph 6.1.3.1). The output of the video system must also be protected against the arcing hazard presented by the CRT.

6.1.3 Signal Processing

The third area of consideration involves signal processing. More specifically, bandwidth, gain control, dc restoration, color balance, shading, blanking, and gamma correction are considered.

Bandwidth. The required bandwidth may be determined from the system timing and resolution requirements. When operating at 180 fields/sec, the active portion of the horizontal scan will last approximately 7.9 μsec. The resolution required is 1024 active picture elements (pixels) per horizontal line.

The highest frequency will occur for alternate pixels being on and off. For this video signal, two pixels make one cycle. This gives a fundamental frequency f_o of

$$f_o = \frac{1024 \text{ pixel}}{7.9 \ \mu\text{sec}} \times \frac{1 \text{ cycle}}{2 \text{ pixel}} \approx 65 \text{ MHz}.$$

The design objective for the video system bandwidth was defined as the fundamental frequency, f_o. If operating at 150 fields/sec, f_o is about 55 MHz.

Gain Gain Control. The input signal level is specified as one volt peak-to-peak minimum. The CRT characteristics require the output drive to the CRT to be up to 80 volts peak-to-peak of video modulation. The maximum gain required is therefore 80. However the gain requirement may be less than 80. To adjust display contrast, a gain control mechanism is required. Since the video system will operate over a very wide bandwidth, the video amplifier is packaged in close proximity to the CRT. The control panel may be physically remote from the area of the CRT. The gain control should therefore provide operation requiring only electrical connection and not rely on a mechanically coupled adjustment mechanism. Gain control range should be as large as possible to provide a satisfactory display under various conditions of ambient illumination.

DC Restoration. In order to accommodate video signals from AC coupled sources, the video system will provide a DC restoration circuit. The circuit will provide actively clamped restoration at the horizontal line rate. That is, during each horizontal retrace period, the bias conditions of the video system will be readjusted so that the voltage appearing at the input will produce an output voltage corresponding to the black (lowest light) level on the display. The circuit will compensate for shifts of up to 20 mV in input signal for consecutive horizontal retrace periods.

Color Balance/Suppression. Since the display is of the sequential color type, with video information presented in three different colors, the video information for the different colors is time multiplexed. That is, information is provided for a red field during a (5.5μsec) field interval. The red field is followed by a green field and then by a blue field, then by the next red field, and so on. In order to select the desired color mixture, a circuit is required which will change the gain of the video system for successive fields. This circuit can also be used to suppress all information presented in a particular color by setting the gain of that field to zero. The gain control which this circuit exercises on any particular color should be independent of control of the other fields.

Shading Correction. One of the topics for consideration in the design of the video system is analog gain control. An input node could be provided at which signals may be mixed to modulate the gain at low frequency (i.e., up to 100 kHz) rates. This is done so that the gain of the video amplifier may be varied as a function of raster position in order to compensate for non-uniformity of illumination in the optics.

Digital Blanking. Another possible feature for the video system is digital blanking. By applying a digital signal, selected portions of the display raster could be blanked.

Gamma Correction. Measurements to determine the gamma (linearity of light output vs input excitation) for the CRT showed the following.

The transfer characteristic of the CRT for the green primary is plotted in Figure 51. The points were plotted assuming a -95 volt grid-to-cathode cutoff voltage. For this assumed cutoff, the points best fitted a straight line on a log-log plot. The slope of this curve is designated as the gamma of the CRT. That is

$$\gamma \ln \frac{(V_{gk} - V_o)}{V_o} = \ln (B/B_o)$$

where V_c is the grid cathode cutoff voltage, V_{gk} is the grid cathode voltage, V_o is a constant with dimension of volts, B is the measured brightness on the display screen, and B_o is a constant with dimension of fL. Rewriting this equation gives

$$\gamma \ln (V) = \ln B/B_o$$

or

$$B = B_o V^{\gamma}$$

where V is a dimensionless quantity proportional to the voltage above cutoff. For the CRT in this display, the value of gamma (γ) is found to be two from the plot. As shown in Figure 6-2 the transfer characteristic for the other primaries (red, blue) has the same general shape. This plot is of normalized values. That is, the points are $\ln (B_n / B_1)$ versus the grid-cathode voltage which produces B_n, where B_1 is the brightness of the primary at a grid-cathode voltage of -72 volts.

The purpose of gamma correction is to cause equal steps of input voltage to cause equal changes in the perceived brightness over the range of brightness values produced on the display. Fechner's Law is an empirically derived formula which states that over a wide range of values of brightness (B), if the relationship

$$\frac{\Delta B}{B} = \text{Constant}$$

is satisfied, then the same sensation of increase in brightness is obtained. If a constant increase in perceived brightness is desired for a constant increment of input voltage then

$$\frac{\Delta B}{B} = \frac{\Delta V_{in}}{V_1}$$

ΔV_{in} is divided by an arbitrary constant V_1 (volts) to make it dimensionless.

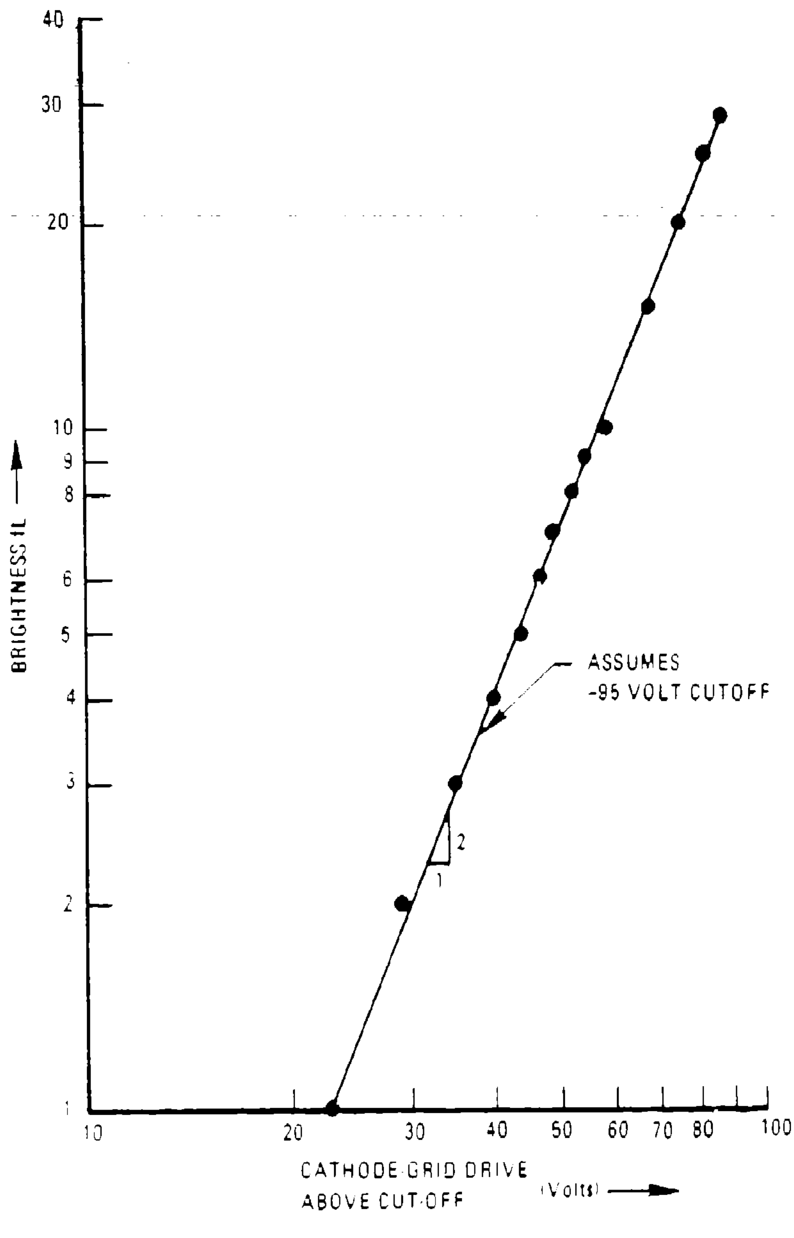


Figure 51 CRT Transfer Characteristic

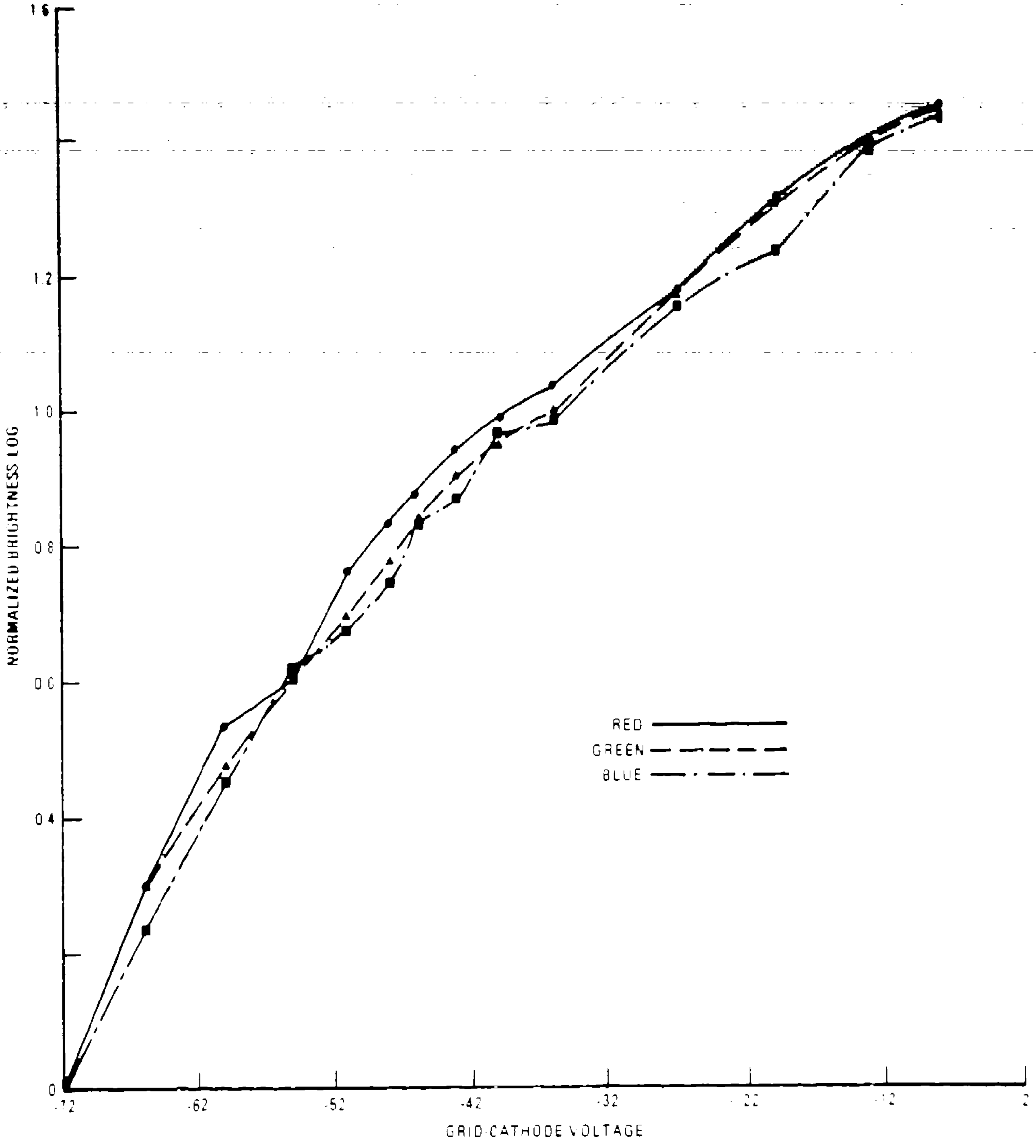


Figure 52 Normalized Brightness vs CRT Drive

Extending to differentials and integrating yields

$$V_{in}/V_1 = \ln B - \ln C$$

or

$$B = C\, e^{(V_{in}/V_1)}$$

The correction applied to V_{in} must be to make

$$C\, e^{(V_{in}/V_1)} = B_o V^{\gamma}$$

Since the value of V_{in} has not been limited, we can assume $V_1 = 1$ volt and since V is proportional to the grid drive above cutoff with some unspecified constant the constants C and B can be absorbed into V to give the simpler equation

$$e^{V_{in}} = V^{\gamma}$$

$$V = e^{(V_{in}/\gamma)}$$

The output voltage of the video amplifier, V_{out}, must then be related to the input voltage V_{in} by

$$V_{out} = k_1\, e^{(V_{in}/\gamma)}$$

if a specified increment of input voltage is to cause the same sensation of change in brightness independent of the initial brightness.

Since the scale of V_{in} is arbitrary, the value of γ can be absorbed into V_{in} and the desired relationship between V_{out} and V_{in} can be expressed as

$$V_{out} = k_1 e^{V_{in}}$$

The same relationship may be deduced from an examination of Figure 51. In order to induce a fixed percentage change in the brightness, the logarithm of the brightness is changed by a fixed increment which corresponds to a fixed increment change in the logarithm of the output voltage, V_{out}, of the video amplifier (grid-cathode drive). Since V_{out} is

derived from V_{in}, fixed increment changes in V_{in} should induce fixed increment changes in the logarithm of V_{out}, i.e.

$$\Delta \ln (V_{out}) = \Delta V_{in}$$

or $\ln V_{out} - \ln k_2 = V_{in}$; k_2 = constant and $V_{out} = k_2 e^{V_{in}}$

The required correction is then independent of the CRT gamma (as long as gamma is constant). The correction should consist of forming an exponential function of the input voltage. An important point to note is that the background brightness level should be established by adding a constant to the input voltage before making the correction. This is because in the expression derived for V_{out}, it is implicit that V_{out} refers to volts about cutoff, so that merely offsetting the grid bias is not the correct method of brightness correction.

6.2 VIDEO PREAMPLIFIER DESIGN

A block diagram of the video preamplifier system is shown in Figure 53.

The video preamplifier provides the interface to external signal sources and performs the signal processing functions of common mode rejection, gain control, dc restoration, and color balance suppression.

Signal processing features addressed but not included in the design are shading correction, digital blanking, and gamma correction. A peripheral circuit was designed to supply inputs to the gain control and color balance supression circuits.

The required inputs to the video system include video signal, horizontal line synchronization pulses, vertical field synchronization pulses, and red field synchronization pulses.

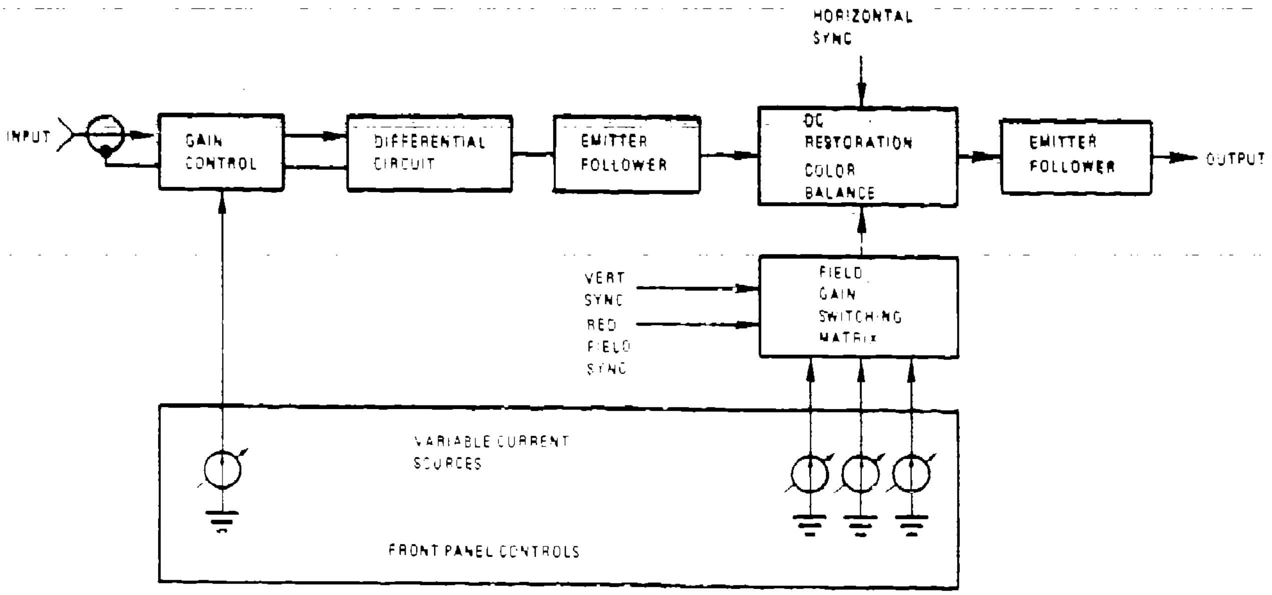


Figure 53 Video Preamplifier System Block Diagram

The overall circuit operation can be described as follows: the input signal is applied to the gain control circuit. This electronic attenuator is controlled by a variable current source which is manually programmable at the front panel of the display.

The gain control circuit provides the same attenuation to the video signal all the time; that is, its action is the same whether the video information appears in a red, green, or blue field. The video return is also carried through the gain control, being acted on with the same gain control function. This is done to maintain the same common mode signal on both inputs to the differential circuit. The differential circuit rejects common mode signals present on the input line and its return. The output of this circuit is a single ended signal which is buffered by an emitter follower and applied to a dual purpose circuit. This dual purpose circuit provides DC restoration and accepts inputs from the field gain switching matrix to produce color balance. Color balance is programmed at the front panel by setting

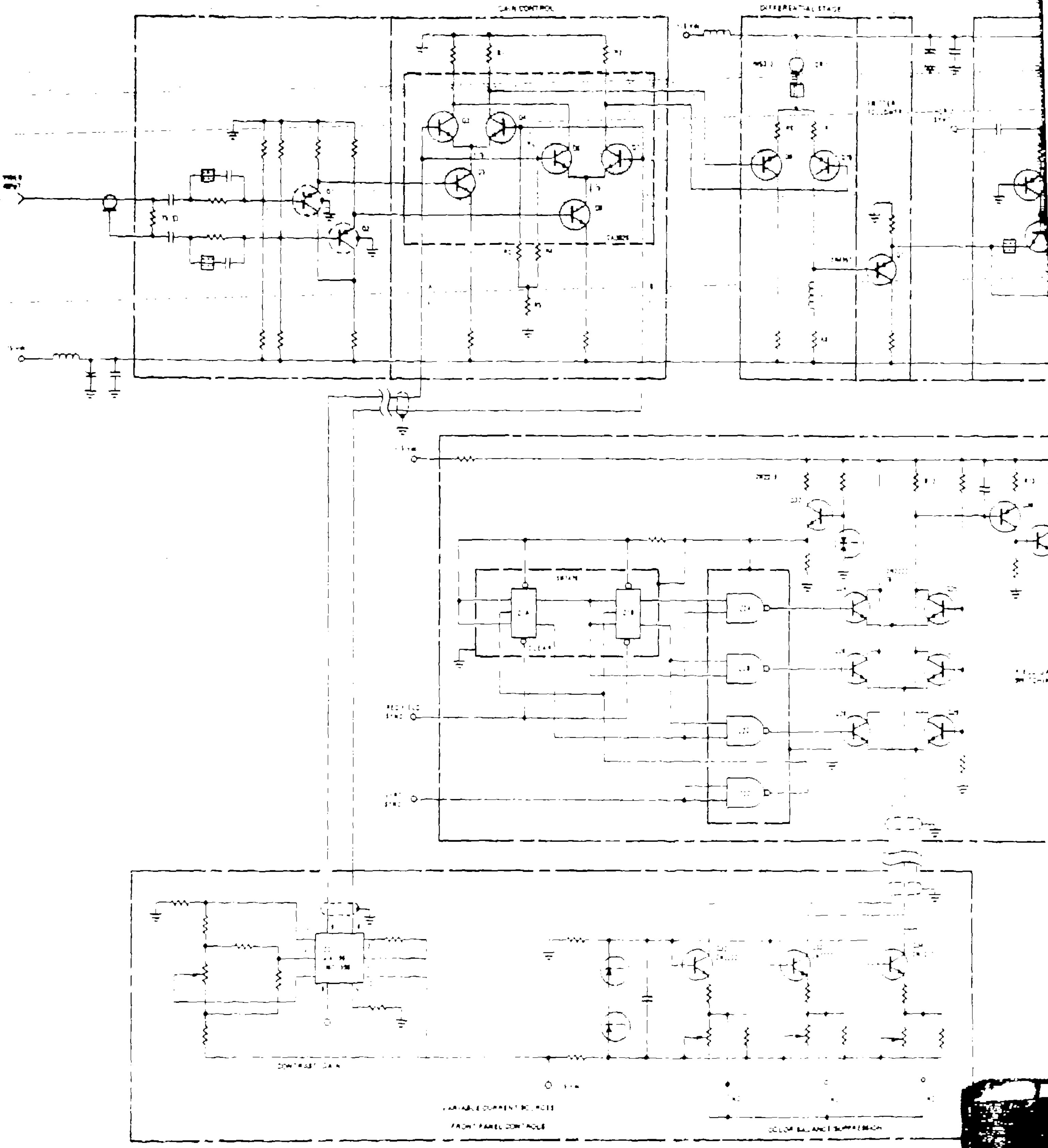
three variable current sources. The level of current from each source determines the relative amplification of the video signal during the fields of one color. By applying the vertical sync and the red field sync to the field gain switching matrix, the signal corresponding to a particular color is applied during the correct fields.

The combination restoration/balance circuit was designed so that the DC restoration condition is not upset by varying the gain of the block. This was done so that shading correction (or some other analog modulation of gain) could be accomplished - even during the active scan - without disturbing the bias condition established by the restoration circuit. Although an analog gain modulation function is not built into the video system, the groundwork for its implementation exists. The horizontal synchronizing pulses applied to the circuit activate a restoration switch during each horizontal retrace period which resets the bias conditions of the preamplifier system to provide the black reference voltage at the output. Video signals received during the following active scan period are presented at the output as variations from this black reference voltage. The DC restoration function is designed so that loss of horizontal sync will cause the output of the preamplifier to assume a level which blanks the display.

Another function, that of digital blankir which is really the extreme case of analog gain control, could also be added at this point by switching the output of the gain switching matrix to a level corresponding to zero gain in the balance circuit at the desired times. The output of the restoration balance circuit is buffered by an emitter follower for application to the output stage.

6.2.1 Detailed Preamplifier Circuit Description

A schematic drawing of the preamplifier is included in the video system schematic of Figure 54. The input to the video system is terminated in 75 ohms, shunted by the input impedance to the first stage of the amplifier. The input impedance to the first stage is maintained at a high level by using emitter follower impedance buffers Q1 and Q2.



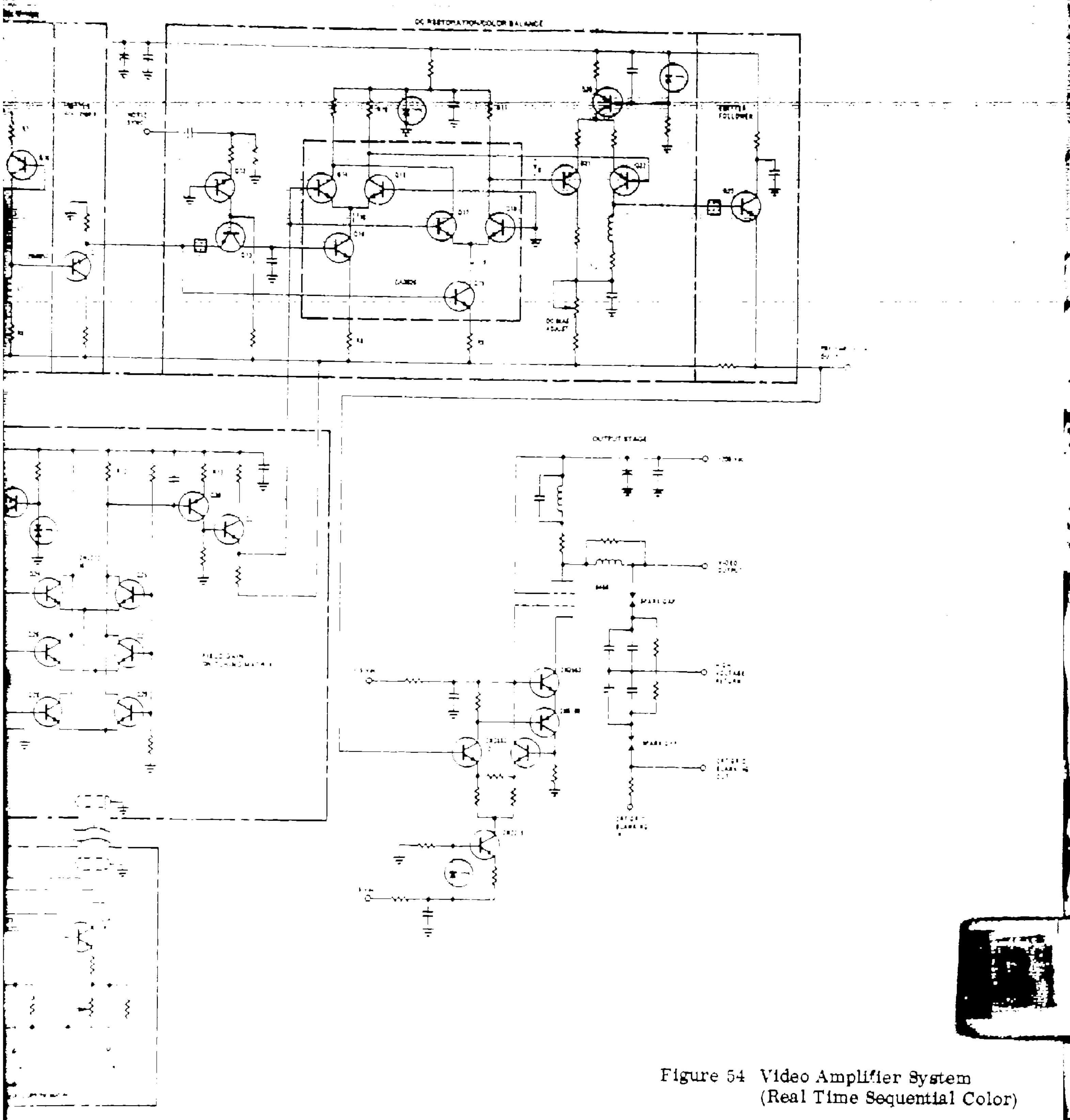


Figure 54 Video Amplifier System
(Real Time Sequential Color)

These emitter followers transmit the input video signal and common mode signal to the gain control circuit. The collector currents of Q5 and Q8 can be denoted I_5 and I_8. Now

$$I_5 = i_s + i_c$$

$$I_8 = i_c$$

where i_s is the component of I_5 caused by the input signal, i_c is the component of I_5 and I_8 caused by the common mode (including bias) voltages.

Consider now the differential pair Q3, Q4. To a very good approximation (see Appendix I) the collector current of Q5 will divide between the emitters of Q3 and Q4 in a ratio which depends only on the difference in base voltages of Q3 and Q4. That is, if the emitter current of Q4 is I_4 then

$$I_4 = \gamma I_5 \quad \text{and} \quad I_3 = (1 - \gamma) I_5$$

where γ is a function only of the differential base voltage ($0 < \gamma < 1$). The collector currents of Q3 and Q4 are proportional (α) to and ($\alpha \approx 1$) nearly equal to the emitter currents. The voltage at the collector of Q4 is V_4

$$V_4 = -R_1 \alpha \gamma I_5$$

Similarly, the voltage at the collector of Q7 is V_7.

$$V_7 = -R_2 \alpha' \gamma' I_8$$

Where the primes on α' and γ' denote possible differences between the two circuits. However, transistors Q3 through Q8 are a monolithic integrated transistor array (CA3026) so that matching and temperature tracking characteristics are nearly perfect. Also, the division ratios γ and γ' are determined by the same differential base voltage.

Therefore $\alpha' \approx \alpha$ and $\gamma' \approx \gamma$. R_1 and R_2 are selected as equal. The differential output from the gain control circuit, $V_7 - V_4$ is then given by

$$(V_7 - V_4) \approx R_1 \alpha \gamma I_5 - R_1 \alpha \gamma I_8 = \gamma(\alpha R_1 i_s)$$

This voltage is proportional to i_s which is proportional to the input signal voltage. Its amplitude is varied by changing γ. This is affected by changing the differential base voltage by varying the currents I_a and I_b. To establish constant bias voltage at the junction of R_3, R_4, and R_5, the sum of I_a and I_b is made constant and (neglecting base currents) that voltage is $-(I_a + I_b) R_5$.

By setting $R_3 = R_4$, the differential base voltage V is

$$V\lambda = R_3 (Ia - I_b)$$

The formation of I_a and I_b is done with Z_3 and surrounding elements. A schematic of this detail is shown in Figure 55. Ignoring base currents, the collector currents of Q7 and Q8 are set by R_o at a value I_o. Assuming Q5 and Q6 are both on, the current through R_e will be I_e given by

$$I_e = \frac{V_{b5} - V_{b6}}{R_e}$$

The voltage $V_{b5} - V_{b6}$ is set using the potentiometer. The collector current of Q5 will then be

$$I_a = I_o + I_e$$

and the collector current of Q6

$$I_b = I_o - I_e$$

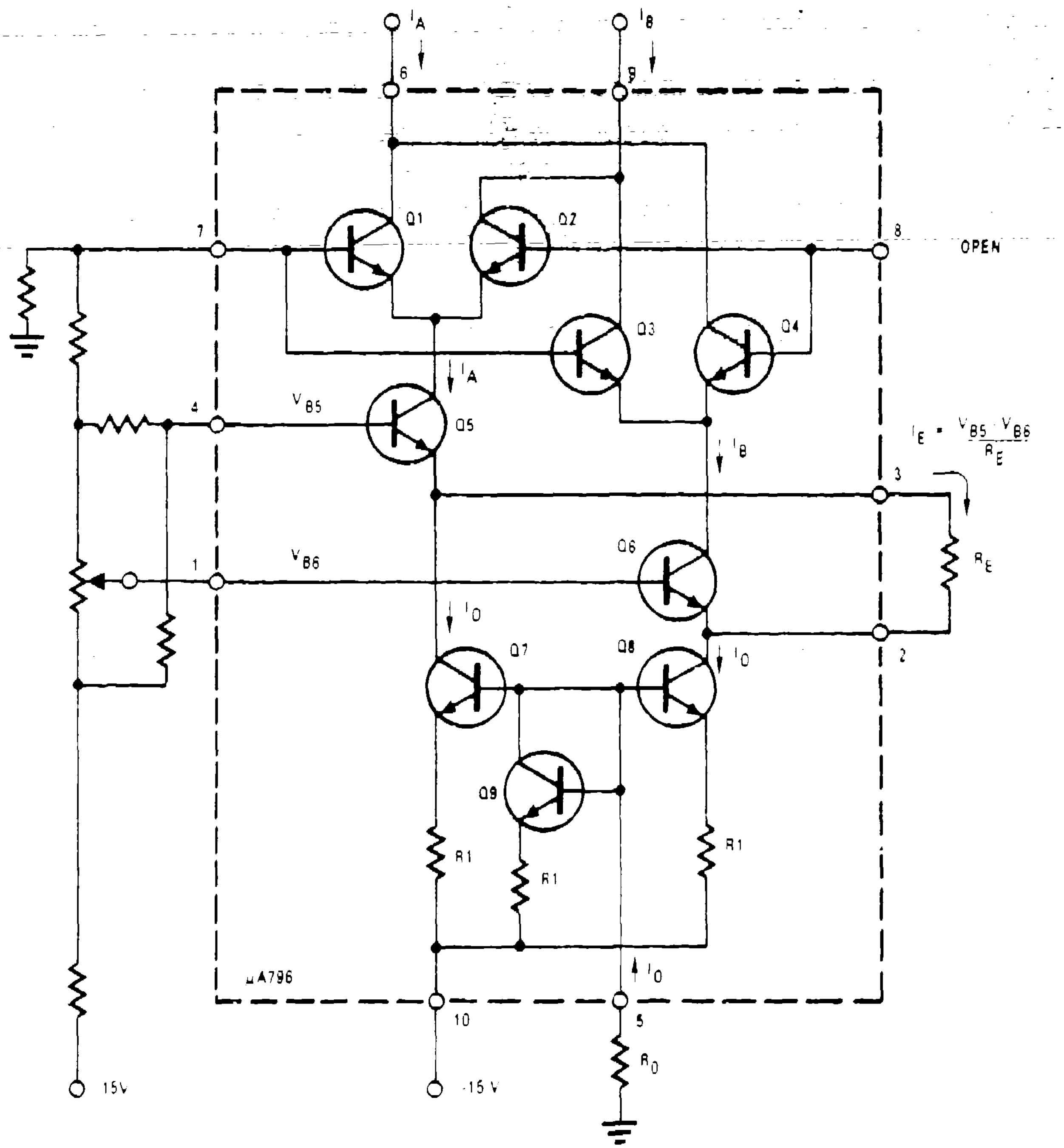


Figure 55 Gain Control Current Generator

Pin 8 of the μA796 is left open while pin 7 is provided with a path for bias current. This turns on Q1 which carries I_a in its collector (pin 6) and Q3 which carries I_b in its collector (pin 9) while turning off Q2 and Q4.

The currents supplied to the gain control circuit are I_a and I_b. Note that as mentioned above, the sum of I_a and I_b is constant.

$$I_a + I_b = (I_o + I_e) + (I_o - I_e) = 2I_o$$

The differential stage follows the gain control circuit. CR1 is a constant current diode (Motorola IN5313) which provides bias current to the differential pair Q9 and Q10. Resistors R6 and R7 are specified as equal and together with R8 set the signal gain of the stage as

$$A_v = \frac{R8}{R6 + R7}$$

The emitter follower, Q11, provides a low impedance drive to the combination DC restoration color balance circuit, the operation of which is described below.

The differential voltage, V_d, is proportional to the difference in collector currents of Q16 and Q19 in the same way as the output differential voltage of the gain control circuit is proportional to the collector currents of Q5 and Q8. Thus if the current flowing in the collector of Q16, I_{16}, is the same as the current which flows in the collector of Q19, I_{19}, when the input voltage is at its black reference level, V_d will depend only on the difference between the voltage appearing on the emitter of Q11 and the voltage which appeared there during the previous horizontal retrace (black reference) period. The current I_{16} is set to the proper level by closing the electronic switch, Q12 and Q13, with the horizontal sync pulses. This sets the base of Q16 at the voltage level which appears on the emitter of Q11 during horizontal retrace (the black reference voltage). The resistors R8 and R9 are set equal. Thus,

$$I_{19} = I_{16} + I_s$$

Where I_s is the portion of I_{19} caused by the deviation of the emitter voltage of Q11 from the black reference level.

In the same way as the output of the gain control circuit was previously described, the voltage V_d is given by (assuming R10 = R11)

$$V_d = -R_{10}\alpha\gamma(I_{19} - I_{16}) = -R_{10}\alpha\gamma I_s$$

The value of γ, $(0 \leq \gamma \leq 1)$, is set by the voltage at the bases of Q14 and Q17. How this voltage is set will be discussed latter. The differential voltage V_d is amplified and brought out single-ended by differential amplifier Q20, Q21, Q22. The collector current of Q20 is constant and, except for the base currents of Q21 and Q22, is passed through the DC bias potentiometer to determine the DC bias level of the pre-amplifier output.

The output of the circuit is taken from the collector of Q22 and is buffered by emitter follower Q23 for application to the output stage.

If the horizontal sync is interrupted the restoration switch (Q12, Q13) remains open and voltage at the base of Q16 will drop towards the negative supply, this reduces the current I_{16} below the black reference level in I_{19}. This action causes the output of the preamplifier to drop below the black reference level (white is positive going at the output of the preamplifier).

The gain control voltage applied to the bases of Q14 and Q17 will be discussed below. By switching the voltage at that point at the field rate, the γ of the circuit can be set to a different value for information appearing in different color fields. The controlling voltage appears at the emitter of Q31. This voltage depends on the current through R12. The current through R12 is selected from the three currents set by the front panel color balance suppression controls. Closing a suppression switch sets a current level which causes the γ factor of the color balance suppression circuit to be zero. The selection is performed by the field gain switching matrix. The switching matrix is composed of current switches (Q24, 25) (Q26, 27) and (Q28, 29). The matrix is driven by gates Z2A, Z2B, and Z2C which decode the outputs of a flip-flop counter Z1A and Z1B which counts vertical sync pulses. The red field sync pulses reset the counter prior to each red field so that the gain selection is synchronized with the video signal.

6.3 VIDEO OUTPUT STAGE DESIGN

The preamplifier is followed by a voltage amplifier to provide the 80-volt peak-to-peak modulation required to drive the CRT. The following approaches to the output stage were considered.

- Distributed amplifier
- Cascode hybrid amplifier
- Amplifier with EBS device

6.3.1 Distributed Amplifier.

A distributed amplifier is depicted in general form as shown in Figure 56.

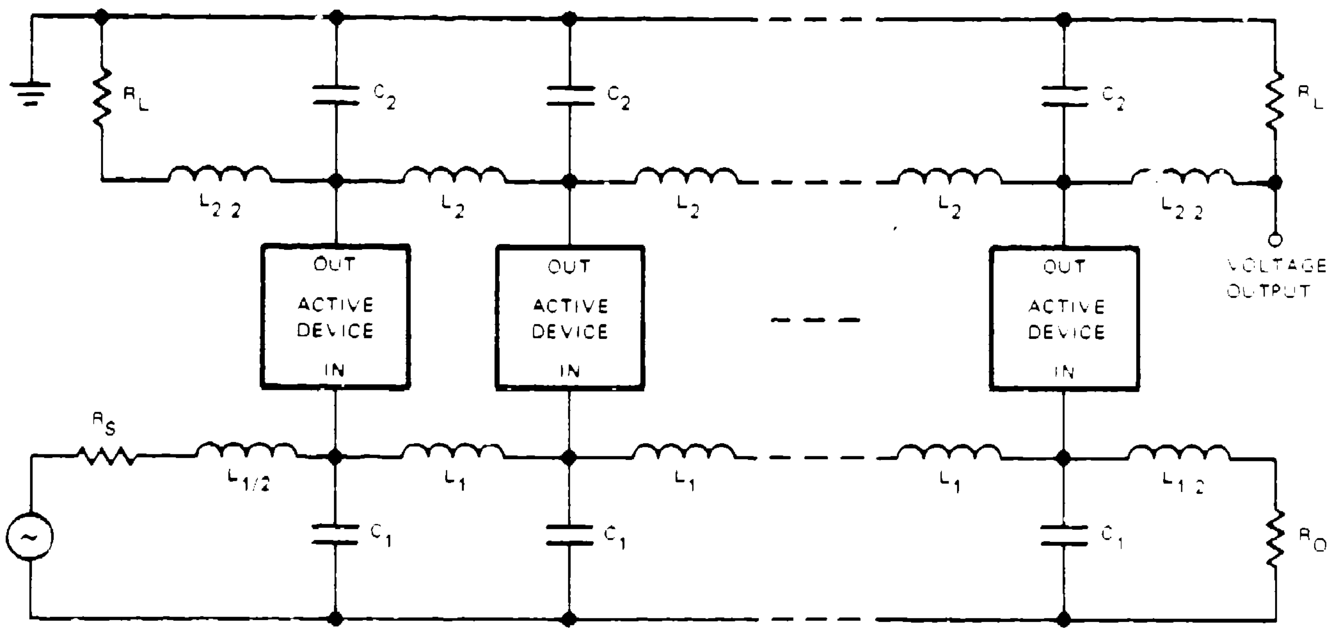


Figure 56 Distributed Amplifier

The value of capacitors C_1 is the input capacitance of the active devices used in the amplifier. The value of capacitors C_2 is the output capacitance of the active devices. The input signal travels down the artificial transmission line of the L_1's and C_1,s at a known velocity exciting each active element in its turn. The group velocity in the output transmission line is selected to have the same value so that the signal produced at the output element of each stage will arrive in phase with the output at each succeeding stage. These outputs will then add directly. The value of the characteristic impedance of the input line is chosen to be R_s, the source impedance from the solid state stage. This will also be the value of R_0. The value of R_L is chosen to be the characteristic impedance of the output line. The output line is terminated at both ends to prevent undesirable reflections.

There is a two-fold reason for selecting vacuum tubes as the active devices in the distributed amplifier involving inadequacies of available solid state devices. At the high bandwidth required, it is almost impossible to provide sufficient protection for transistors capable of dissipating the power required to generate the high level, wide bandwidth signals required.

A review of the literature* and preliminary calculations showed that for a distributed amplifier to accomplish the required gain would involve up to 12 active devices; probably power tetrodes. Such a design would be very complex and the chance of success limited.

6.3.2 Cascode Hybrid Amplifier

The cascode hybrid amplifier employing a tetrode output is depicted in the block diagram (Figure 57). The high level current I_1 which is formed in the transconductance block is linearly related to the input voltage and is passed through the cathode of the tetrode, which is operating in the grounded grid configuration. This current then passes to the peaked load which has both series and shunt compensation.

The peaked load is optimized to match the input capacitance of the CRT. A vacuum tube device was selected for the output in this stage for substantially the same reasons as in the distributed amplifier.

*M.S. Ghausi, Principles and Design of Linear Active Circuits, Chapter 13, McGraw-Hill, 1965

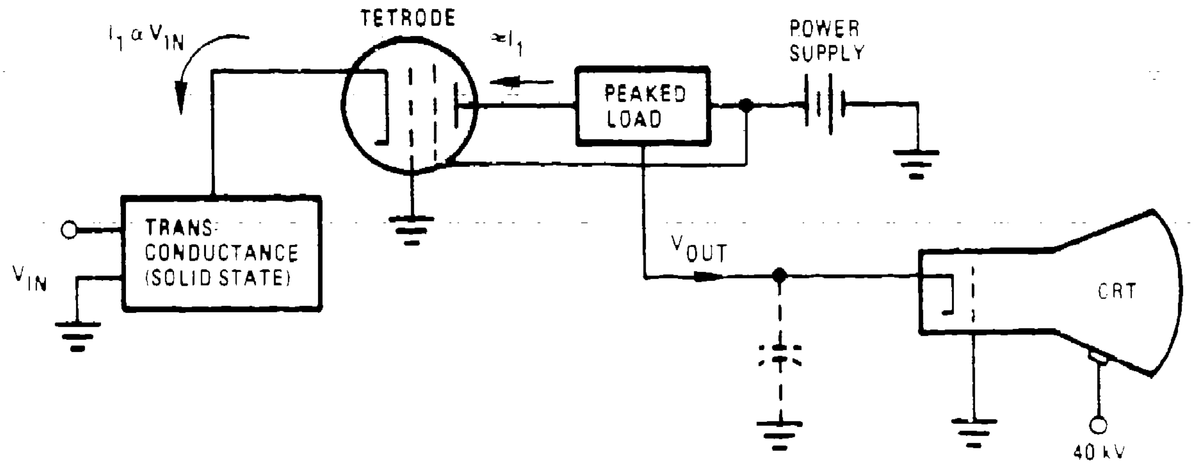


Figure 57 Cascode Hybrid Amplifier Block Diag.am

Amplifier with EBS Devices. A most promising output circuit for high level, extremely fast video amplification employs an electron beam semiconductor (EBS) device (See Figure 58). In such a device, a reverse biased diode is bombarded with a low-current high-energy electron (10 Kev) beam. As each high-energy electron surrenders its energy in the diode, it creates multiple pairs of carriers. These current pairs are rapidly swept out of the depletion region of the diode by the field set up by its reverse bias voltage. This current is passed through a load resistor to create the voltage output. Linear amplification at extremely high speeds is accomplished by deflecting a rectangular electron beam partially onto the diode. The portion of the beam which illuminates the diode is proportional to the voltage applied to deflection plates placed between an electron gun and the diode. EBS Video amplifiers with output modulation in excess of 100 volts and rise times of less than 2 nsec have been built at the laboratories of Watkins-Johnson where EBS devices are currently under development. At the present time, the cost of a single EBS device is prohibitive ($5K) because of their developmental status. However, these devices should go into regular production in the next 2 to 4 years at which time the price should drop below $500 per device.

The required drive for the 50 ohm deflection system is on the order of 5 volts to produce 80 volts of modulation with a 50 ohm load resistor. (See Figure 59).

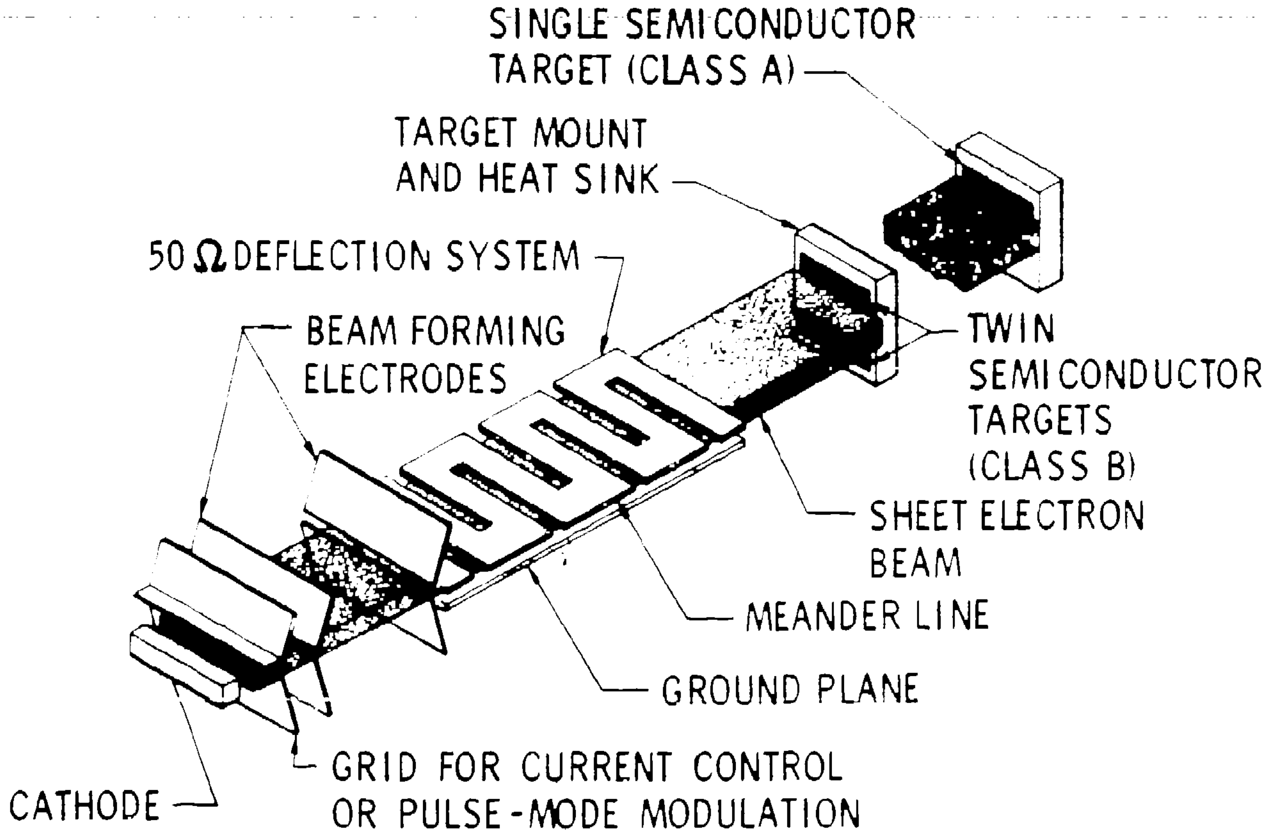


Figure 58 Schematic Arrangement of Elements in a Deflected Beam EBS Amplifier

Horizontal Sensitivity: 4 ns/div.

Vertical Sensitivity:
Top Trace - 10V/div.
Bottom Trace - 50V/div.

Figure 59 Comparison of Input and Output Pulses of WJ-3650 EBS Amplifier with 50 Ohm Load Resistance

This drive could be readily provided with solid state circuitry. An additional power supply (10kV) would have to be added to the display system to accommodate the EBS amplifier.

Even though the EBS device has a solid state output, it can dissipate high levels of power. It can also carry large amounts of current and it is thought that it can be protected from the arcing hazard of the CRT.

Choice of Output Stage for Implementation. The type of output stage selected is the hybrid cascode amplifier. This selection was based on the cascode amplifier's simplicity compared to the distributed amplifier and the fact that it uses active devices which are readily available. The EBS amplifier looks very promising but the active device is still in its development stage.

6.3.3 Description of Cascode Output Circuit

The cascode output circuit is depicted in Figure 60. Transistor Q3 is a current source for the differential pair Q1, Q2. The resistors in the emitter circuits of Q1, Q2, are very small. An increase in the video input voltage causes an increase in the collector current

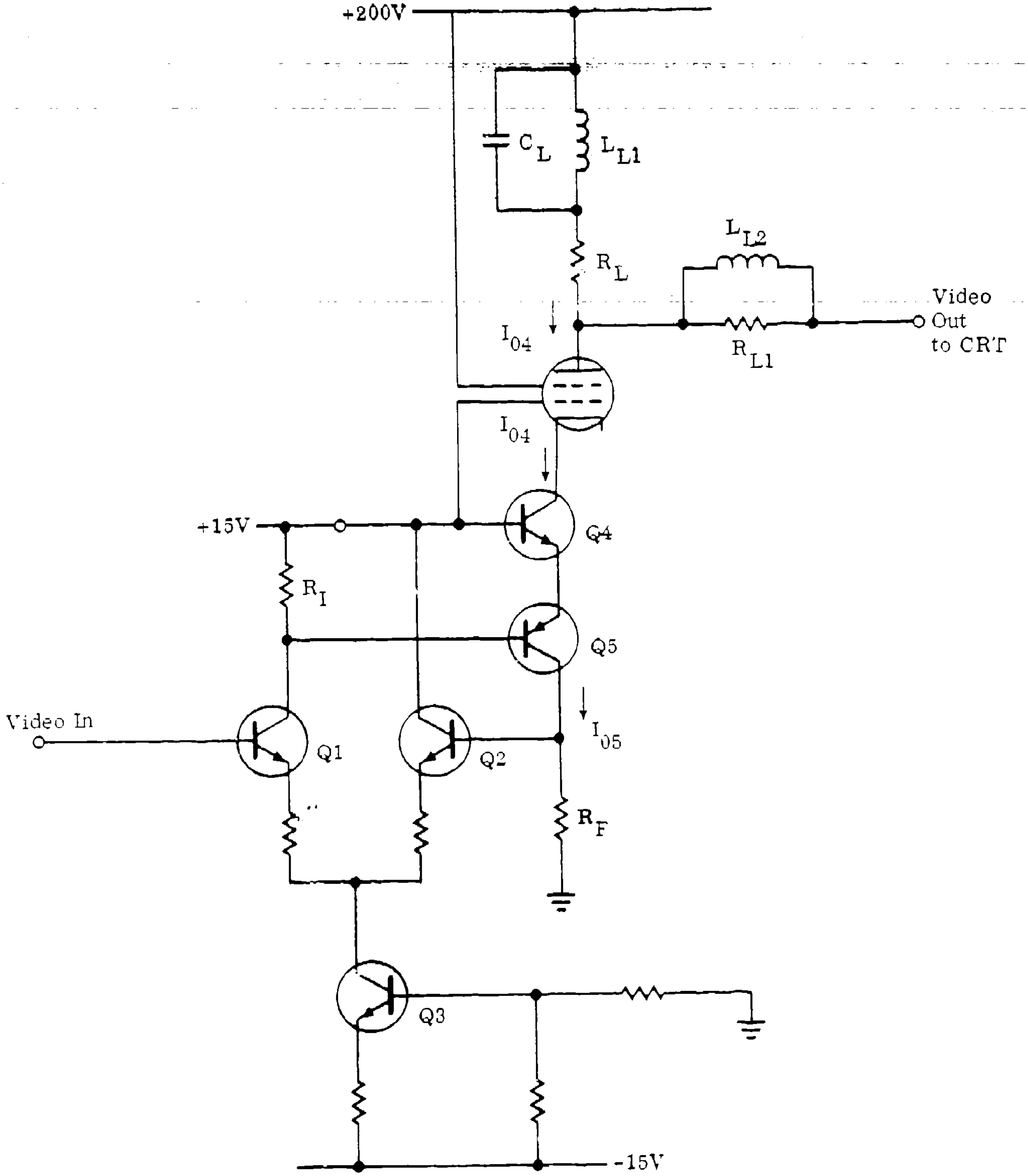


Figure 60 Cascode Output Amplifier

of Q1 which increases base drive in Q5. This causes collector current of Q5 to increase. Enough gain is provided that very large currents can develop in the collector of Q5. A feedback connection is made to the base of Q2 with voltage developed across R_F. This feedback causes the base voltage of Q2 to track the video input voltage. As a consequence, the collector current of Q5, I_{05}, is given approximately by

$$I_{05} \approx V_{in}/R_f$$

And except for base currents

$$I_{04} \approx I_{05} \approx V_{in}/Rf$$

The tetrode is operated in cascode - that is, it passes the current I_{04} to the load while isolating Q4 from the load. This isolation accomplishes two necessary results: 1) it permits the load current to be developed at low power in the solid state transconductance amplifier and 2) it protects the solid state circuitry from the arcing hazard of the CRT.

The voltage gain of the output stage is roughly

$$A_v \approx R_L/Rf$$

Actually, the gain is somewhat less than this because the gain of the transconductance amplifier is lowered by base current losses. The output load element values, R_L, R_{L1}, L_{L1}, L_{L2}, C_L are determined by bandwidth requirements and the capacitances which appear at the plate of the tetrode and in the load (strays + CRT cathode capacitance). For discussion purposes, it is simpler to use risetimes than bandwidths. The relationship between 3dB video bandwidth B and 10-90% risetime, t_r, in a circuit such as Figure 31 is given by

$$t_r B = k \quad , 0.35 < k < 0.45$$

Where k depends on the particulars of the peaking. In a system with no peaking $k \approx 0.35$ while in a system with a lot of peaking $k \approx 0.45$ (See Figure 59).

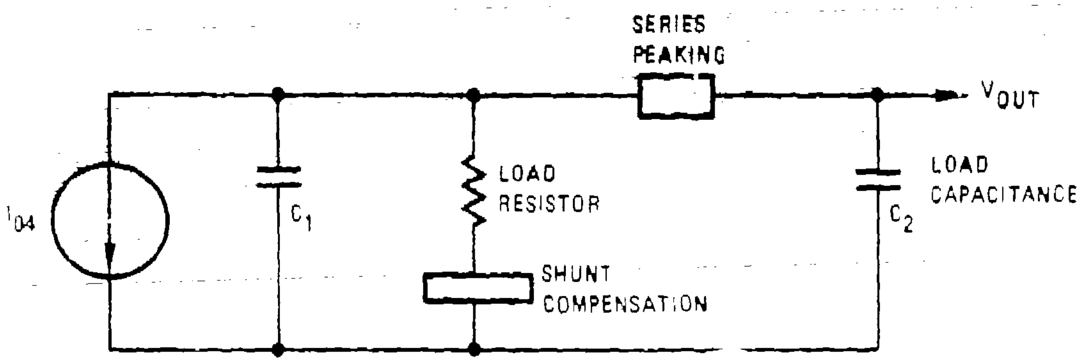


Figure 6-11 Peaked Circuit

That $k = 0.35$ for the non-peaked circuit is easily demonstrated. With the compensation elements shorted, the current source drives a load of $(C_1 + C_2)$ in parallel with R_L. The 10-90% risetime of the voltage output for a step in I_{04} is

$$t_r = 2.2\, R_L\, (C_1 + C_2)$$

while the 3dB bandwidth is

$$B = \frac{1}{2\pi R_L\, (C_1 + C_2)}$$

The product is

$$t_r B = \frac{2.2\, R_L\, (C_1 + C_2)}{2\pi R_L\, (C_1 + C_2)} = \frac{2.2}{2\pi} \approx 0.35$$

One of the factors considered in designing the output stage was minimizing power consumption. For this reason it is desirable to make R_L as large as possible. At the required bandwidth of 65 MHz a risetime of

$$t_r = \frac{0.45}{65 \times 10^6} \text{ sec} = \frac{450}{65} \text{ usec}$$

$$\cong 7 \text{ nanoseconds.}$$

is required.

The load capacitance is about 10pF (8pF for the CRT and 2pF strays). A tetrode with output capacitance no greater than 9pF is realistic.

The uncompensated risetime would be

$$(t_r)_u = 2.2\, R_L\, (19_{pF})$$

For moderate peaking, the risetime can be improved by a factor of 1.8. The uncompensated risetime can therefore be 1.8 times as large as the required risetime.

$$(t_r) = 1.8\ (7 \text{ nanoseconds}) = 2.2\, R_L\, (19_{pF})$$

$$R_L = \frac{12.6}{41.8} \text{ K } \Omega = 300\Omega$$

The notion of peaking video amplifiers has been investigated extensively. A good review of the subject is found in Electronic Amplifier Circuits by Pettit and McWhorter (McGraw-Hill, 1961). The following network was taken from that book and used for preliminary specification of the peaking network. (See Figure 62).

The values selected were (refer to amplifier schematic, Figure 60)

$R_L = 300\Omega$ $\quad$ $L_{L2} = 1\mu H$

$C_L = 5pF$ $\quad$ $R_{L1} = 1.1K$

$L_{L1} = .2\mu H$

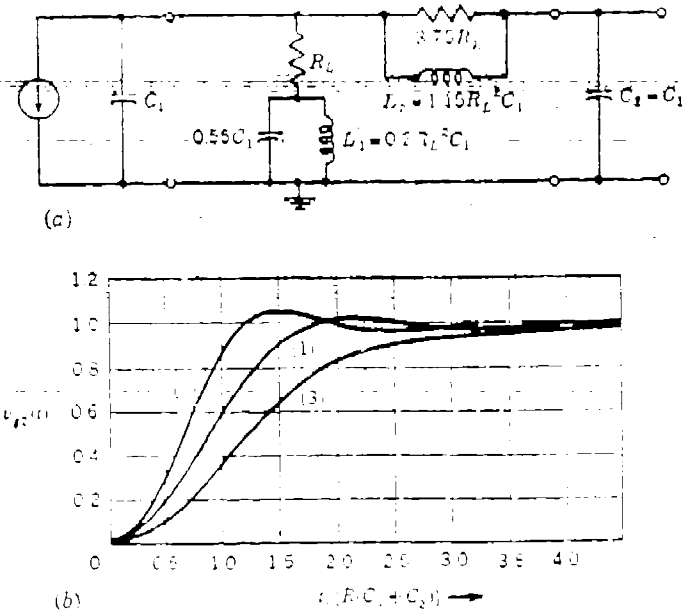


Figure 62 Four-terminal Network Designed for $C_1 = C_2$. (a) Circuit.
(b) Step Response for (1) $C_2 = C_1$, (2) $C_2 = C_1/2$, (3) $C_2 = 2C_1$.

6.4 HARDWARE RESULTS

Several photograph are included in this section to illustrate operation of the video system. Aspects to be illustrated include gain control, common mode rejection, dc restoration, color balance control, system pulse response, system bandwidth.

Diagrams of test setups are provided when necessary to show the conditions which cause the waveforms in the photographs.

All tests are conducted in the display using the synchronizing pulses from the internal pattern generator. The pre-amplifier is configured as shown in the block diagram of Figure 53.

Gain Control - The video input is the vertical bar pattern from the pattern generator. The input is shown in the upper trace of Figure 63. The lower trace is the waveform at the output of the emitter follower between the differential circuit and the DC restoration/color balance circuit. This lower trace is a multiple exposure with the front panel gain control set to four different positions.

Common Mode Rejection. To test the common mode rejection characteristics of the system, the output of a test oscillator is applied to both the input and return for the input of the system. For this test, the gain control is set to maximum. The input for a typical case is shown in the upper trace of Figure 64. The lower trace is the output of the emitter follower between the differential stage and the DC restoration color balance circuit.

The common mode rejection is defined in dB by the equation

$$\text{CMR} = 20 \log_{10} \frac{\text{CM input signal level x gain to point of measurement}}{\text{CM signal level at point of measurement}}$$

Horizontal: 5 μsec div.

Vertical: Upper: 2V div. — Input; Lower: 1V div. — Output; DC Coupled

Figure 63 Gain Control

Vertical: Upper: 1V/div.
Lower: 50 mV/div.

Horizontal: 0.5 msec/div.

Figure 64 Common Mode Rejection

For the case shown the input common mode frequency is 400 Hz, that of the input power.

$$\text{CMR} = 20 \log_{10} \left(\frac{2\ V_{pp} \times 1.25}{5\ mV_{pp}} \right)$$
$$= 54\ \text{dB}$$

<u>DC Restoration.</u> DC restoration is demonstrated by selecting the test pattern of Figure 65, with the pattern generator.

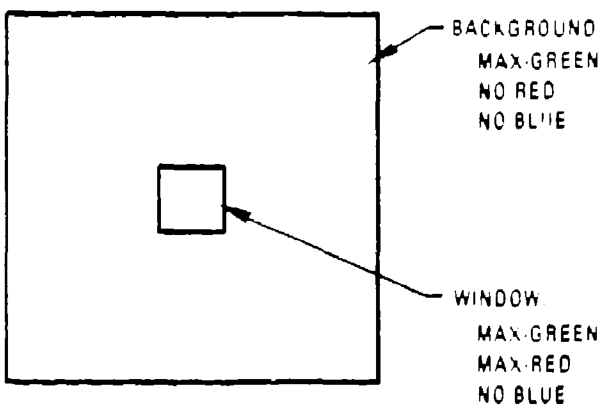


Figure 65 Test Pattern

During the green field, the input video looks like Figure 66.

During vertical retrace and the blue field, the video signal goes to zero. Its average value during these times is the black level.

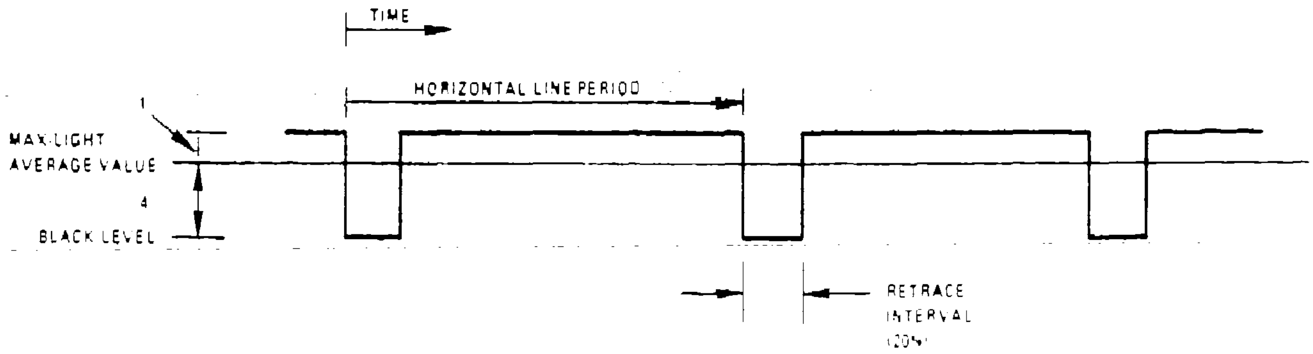


Figure 66 Input Video During the Green Field

During most of the red field, the video signal also goes to the black level. However, the few lines which contain the window will look like Figure 67.

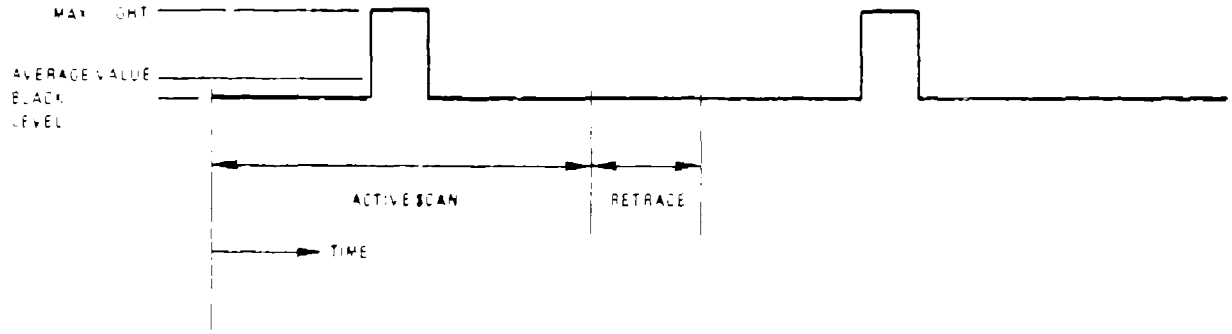


Figure 67 Video Signal During Most of the Red Field

The signal is ac coupled at the input. So at the output of the differential circuit the average value of the video signal will tend toward a value set by the bias networds. The average value at the input during each color field is shown in Figure 68.

After ac coupling, the average value of the video signal will be established and the average value during individual fields will tend toward this value with time constants determined by coupling networks. This is illustrated in Figure 69.

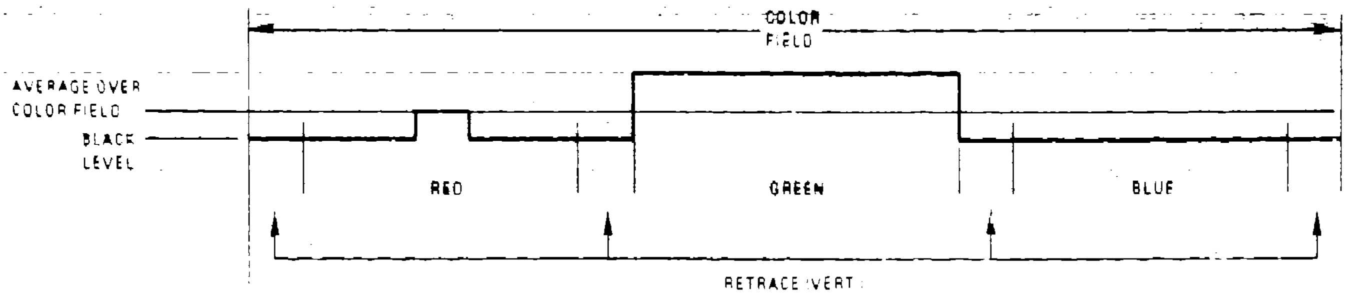


Figure 68 Average Value at the Input During Each Color Field

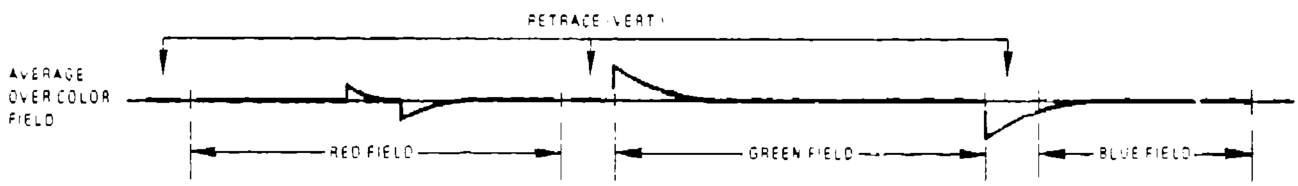


Figure 69 Average Value of Video Signal

Prior to DC restoration the black level is referenced to the average value by the voltage of the black level with respect to the average value. Thus, the black level before DC restoration has a waveform like that in Figure 70.

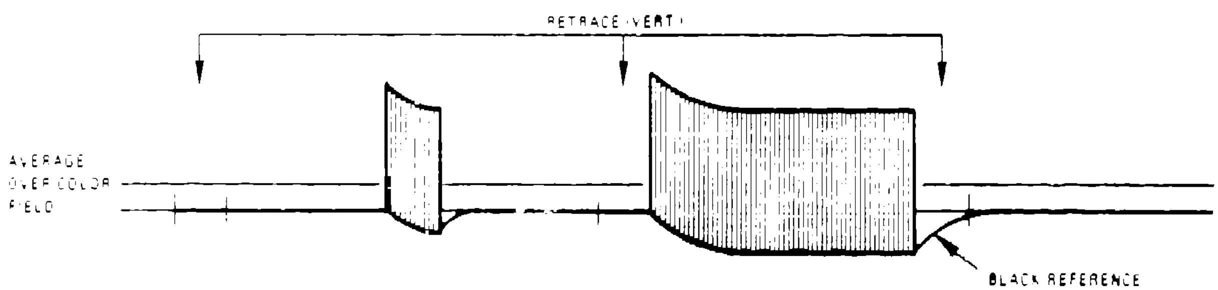


Figure 70 Waveform of Black Level Before DC Restoration - AC Coupled Video Signal

This signal appears inverted at the emitter of Q11, and is shown in the photograph, Figure 71.

Note that the time constants are actually much longer than those shown in Figure 70, which makes the rate of change of unrestored black level appear to vary almost linearly with time when there is a transient change in the average value.

The purpose of the dc restoration is to remove the variations in the black reference and establish a constant DC level for the black reference. The effectiveness of the circuit is illustrated by the photograph (Figure 72), which shows the output of the pre-amplifier at the emitter of Q23.

<u>Color Balance.</u> Photographs are included to show the action of the color balance circuit. The input signal is shown in the lower trace of Figure 73. This is the signal which appears during each active horizontal line regardless of the color field in which it occurs. The upper trace is the output of the video system with the color balance controls set to give different gain in fields of different colors.

<u>System Pulse Response.</u> The pulse response was tested using the vertical bar pattern of the pattern generator. The lower trace of the photograph of Figure 74 is the input pulse and the upper trace is the output of the video system. For this test, the CRT is disconnected and the system is loaded with the oscilloscope probe (Tektronix P6047) which has a capacitance of 10 pF and is therefore approximately the same load as the CRT.

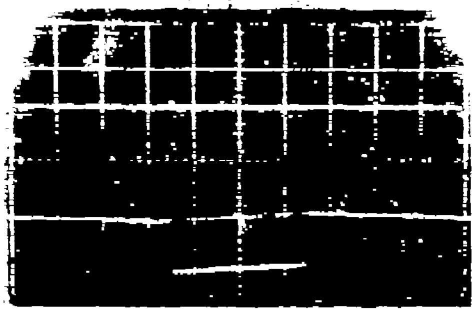
Measured risetimes for the video system are on the order of 8 nsec. For the approximation of risetime bandwidth product in a peaked circuit,

$$t_r B = 0.45$$

The bandwidth is

$$B \approx 56 \text{ MHz}$$

As shown in Section 6.1.3, this is sufficient bandwidth for the 150 field sec mode of operation.

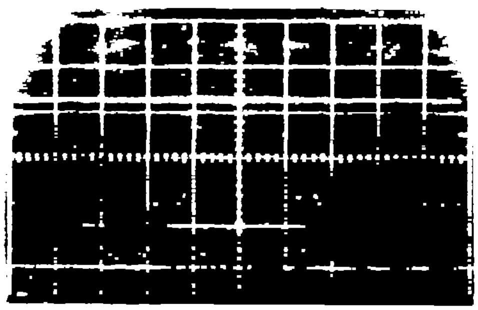


Horizontal: 2 msec/div.

Vertical: Upper: 5V/div. } Red Field Sync Pulses

Vertical: Lower: 5V/div. } Unrestored Video

Figure 71 Unrestored Video

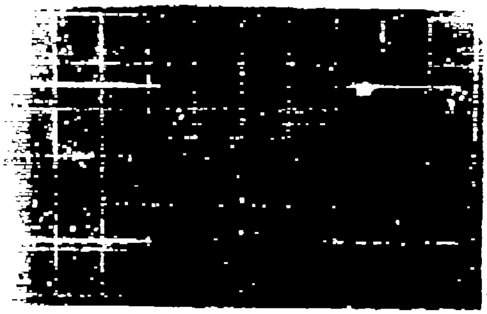


Horizontal: 2 msec/div.

Vertical: Upper: 5V/div. } Red Field Sync Pulses

Vertical: Lower: 1V/div. } Restored Video

Figure 72 Restored Video



Horizontal: 200 nsec/div.

Vertical: Upper: 50V/div.
Lower: 1V/div.

Figure 73 Color Balance Control

Horizontal: Upper: 50V div. - Output
Lower: 1V div. - Input

Vertical: 50 nsec div.

Figure 74 System Pulse Response

System Bandwidth. The system Bandwidth is tested using the setup shown in Figure 75.

The Photographs show the input, Figure 76, and the output, Figure 77.

As seen from the photograph of the input voltage trace the input signal starts rolling off at around 50 MHz. This is due to the characteristics of the Ball Brothers Mark 81 video mixer. This equipment was required to insert blanking during horizontal retrace. Even with the input roll off, the photographs can be used to approximate the -3 dB bandwidth of the video system by taking into account the roll off of the input when examining the output. The bandwidth is estimated from the photographs to be approximately 55 MHz, which agrees well with the risetime measurements.

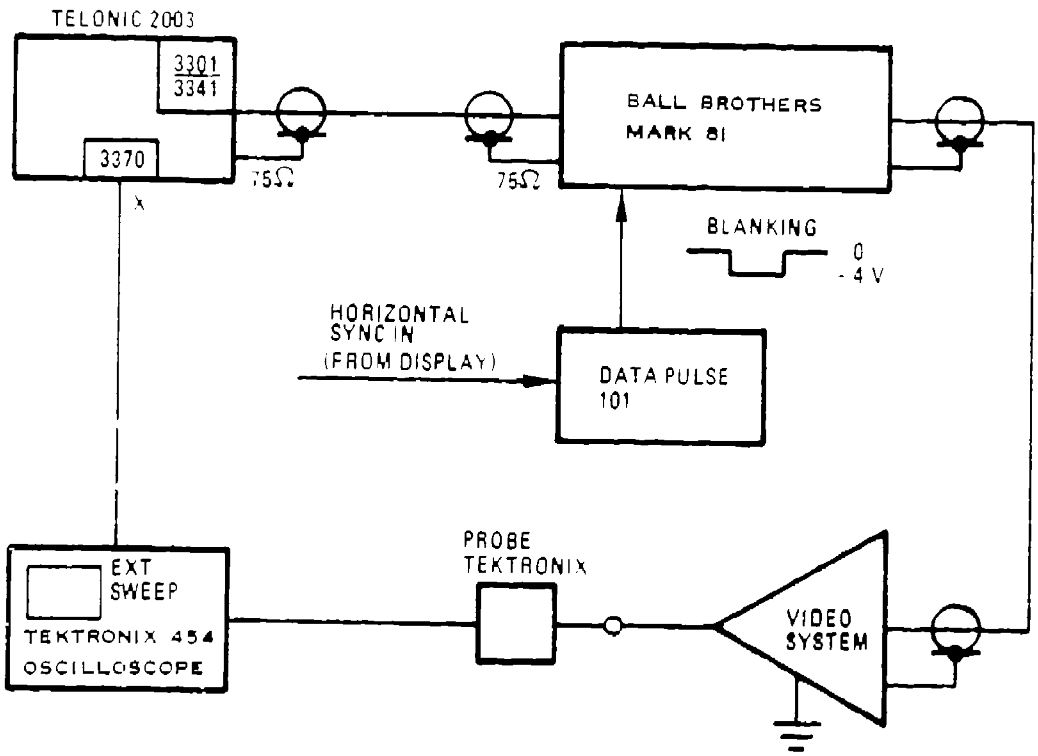


Figure 75 Test Setup for System Bandwidth

Vertical: 0.5V/div.
Horizonatal: 0-70 MHz

Figure 76 Bandwidth Response: Input

Vertical: 20V div.
Horizonatal: 0-70 MHz

Figure 77 Bandwidth Response: Output

SECTION 7

DEFLECTION SYSTEM

7.1 DEFLECTION CIRCUITS

The deflection circuit design was one of the major tasks to be developed under this study. The original block diagram proposed is shown in Figure 78.

The vertical deflection technique proposed was straight forward. It consisted of a standard ramp generator driving a linear amplifier. This amplifier design had been successfully proven in existing Philco-Ford tactical display equipment.

A difficult design problem existed for the horizontal deflection system. Because the system is sequential color, the scan speed must be approximately three times as fast as a conventional single color CRT display of the same resolution. The result is a horizontal line period of about 10 microsecond, with 8 microseconds for the scan and 2 microseconds for the retrace. Since a resonant technique was selected, the difficulty existed because of the large energy transfer required to reset the coil in the short retrace period.

To understand the development of the design, the following specifications and design goals should be reviewed.

7.2 DESIGN GOALS AND SPECIFICATIONS

The specifications for deflection must be consistent with the basic design goal of achieving a three color, sequential field, high-resolution (1000 x 1000 element), CRT raster scan display. Utilizing thirty complete frames per second, three color frames per complete frame and two fields per color frame, the following timing requirements result:

Three color frames in 1/30 sec

Time color frame = 1/90 sec = 11.1 milliseconds

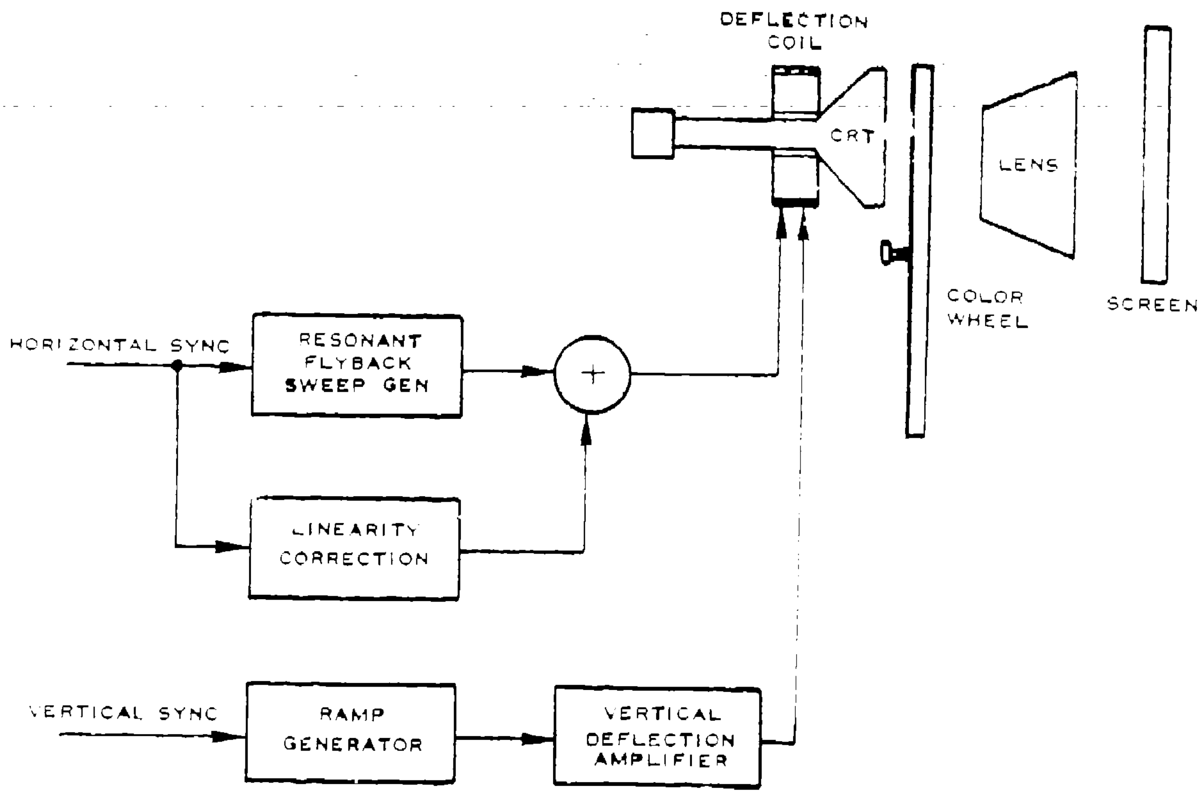


Figure 78 Deflection Circuit Design Block Diagram

Time per color field = 5.55 milliseconds

1000 to 1024 active scan lines/color frame

1125 total horizontal scan lines/color frame

$\therefore$ Vertical retrace $= \frac{100}{1125} \cong 0.09 = 9\% = (0.09)(5.55) \cong 0.5$ milliseconds

Vertical scan time $\pm$ 5.55-0.5 = 5.05 msec

Horizontal period $= \frac{11.1 \text{ milliseconds}}{1125} = 9.87$ msec

Horizontal retrace = 20% of horizontal period = (0.2) (9.87) = 1.97 msec

Horizontal scan time = 9.87 - 1.97 = 7.9 msec

With these timing requirements the next specification which defines the usefulness and aesthetic quality of the display image relates to linearity. In general terms, the linearity defines the limit of error that can be tolerated in the placement of a spot (or element) on the CRT from the ideal true position. The linearity requirement for this display was set at 2%. This value was determined to be an optimum compromise between the usefulness to the viewer and the relative difficulty in achieving higher linearity. The amount of linearity correction required for a particular application is mainly a function of the following physical variables: the winding configuration and material of the deflection yoke, the angle of deflection required for proper size of the display, and the faceplate curvature of the CRT.

7.3 CIRCUIT DEVELOPMENT

7.3.1 Vertical Deflection

The vertical sweep system consists of three main active-circuit networks and the vertical deflection windings of the yoke, as shown in the block diagram of Figure 79.

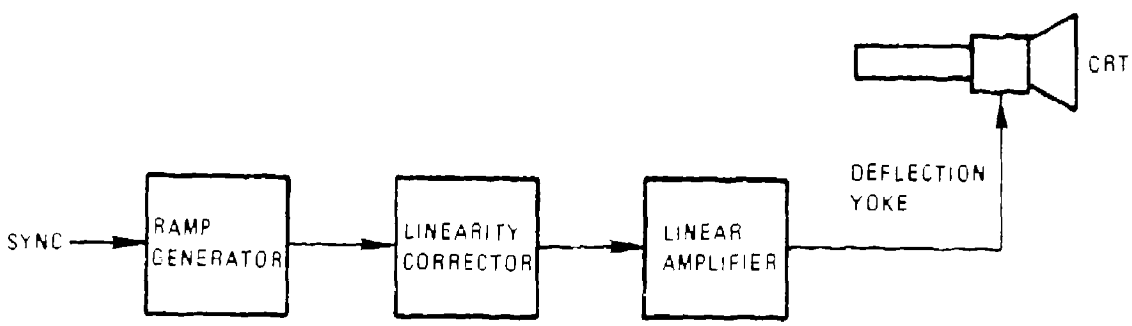


Figure 79 Vertical Sweep System

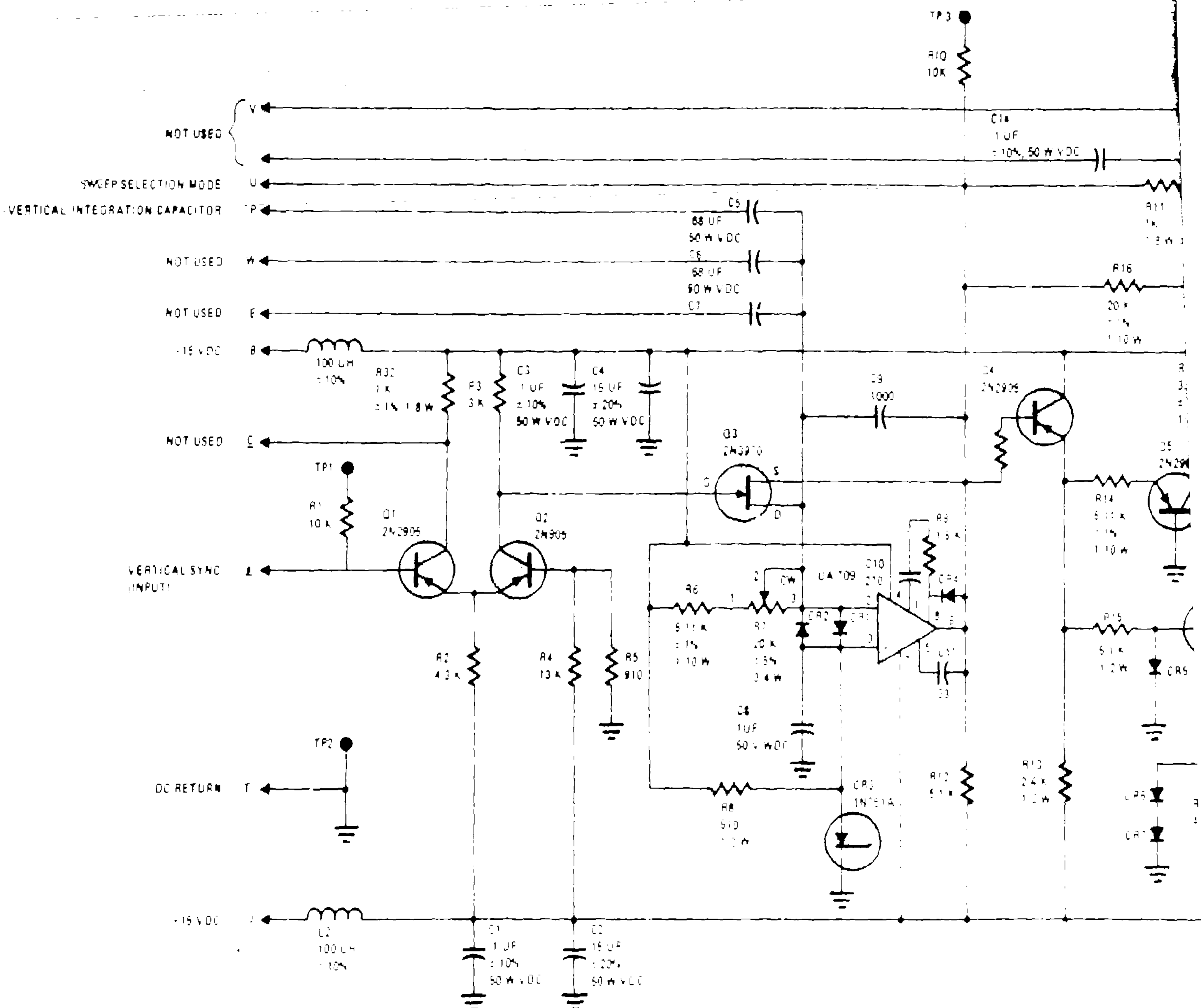
The ramp generator and linearity corrector are contained on the same printed circuit board (joint schematics are shown in Figure 80; the schematic for the linear amplifier is shown in Figure 81).

The ramp generator consists of Q1, Q2, Q3 and Z1 and operates by charging capacitor (C5) with a constant current source (R6, R7) to obtain a linear ramp and discharging the capacitor with a semi-conductor switch (Q3) to reset the voltage to its initial condition. Q1 and Q2 provide a dc level shift and amplification of the sync pulse which turns Q3 OFF for the linear ramp and ON for reset. Z1 is a high-gain operational amplifier which operates as an integrator and develops the linear ramp on (C5) and provides a low-impedance drive for the linearity corrector.

The linearity corrector consists of Q4, Q5, Q6, Q7, Q8, and Z2. Z2 is a high-gain operational amplifier that is connected to invert and amplify its input by a factor of 100. The input to Z1 is developed across Q8 and R24. With Q8 turned off the series combination of R16 and R24 provide a voltage divider with the ratio $\frac{249}{20249} = 0.012$ for the signal on the output of Z1. With Q8 turned partially on this ratio becomes proportionately smaller. Thus Q8 operates on the signal input to Z2 and forms a modified ramp with "S" curve correction. Q4, Q5, Q6, and Q7 develop the input signal to Q8 which is shown in Figure 82.

The amplitude (A) of this wave form is controlled by R21 which in turn determines the degree of curvature of the "S" curve. The dc offset (B) is controlled by R23 which in turn determines the points of inflection of the "S" curve.

The linearity correction produced by this method is known as "on axis" linearity correction because the correction waveform is only a function of the one axis of deflection and does not account for the position of the spot in the orthagonal axis. Thus, without further correction the raster would extend its corners and would have the appearance of a pincushion. For this reason, a secondary magnetic field is produced by a pincushion corrector. This coil is mounted to the deflection yoke at the CRT faceplate end and produces a static magnetic field that opposes the deflection yoke field in the corners and aids the on-axis deflection yoke field. This provides the desired off-axis correction and the ability to obtain a raster with less than 1% of linearity distortion.



NOT USED
SWEEP SELECTION MODE
VERTICAL INTEGRATION CAPACITOR
NOT USED
NOT USED
+15 VDC
NOT USED
VERTICAL SYNC (INPUT)
DC RETURN
-15 VDC
TP3
R10 10K
C14 1 UF ±10%, 50 W VDC
C5 68 UF 50 W VDC
R16 20 K
100 UH ±10%
R32 1 K ±1% 1/8 W
R3 3 K
C3 1 UF ±10% 50 W VDC
C4 15 UF ±20% 50 W VDC
C9 1000
Q4 2N2905
Q3 2N3970
TP1
R1 10 K
Q1 2N2905
Q2 2N905
R14
R6
R7 20 K
UA 709
C10
R2 4.3 K
R4 13 K
R5 910
C8 1 UF
TP2
R8 510
CR3 1N751A
R13 2.4 K
L2 100 UH
C1 1 UF ±10% 50 W VDC
C2 15 UF ±20% 50 W VDC

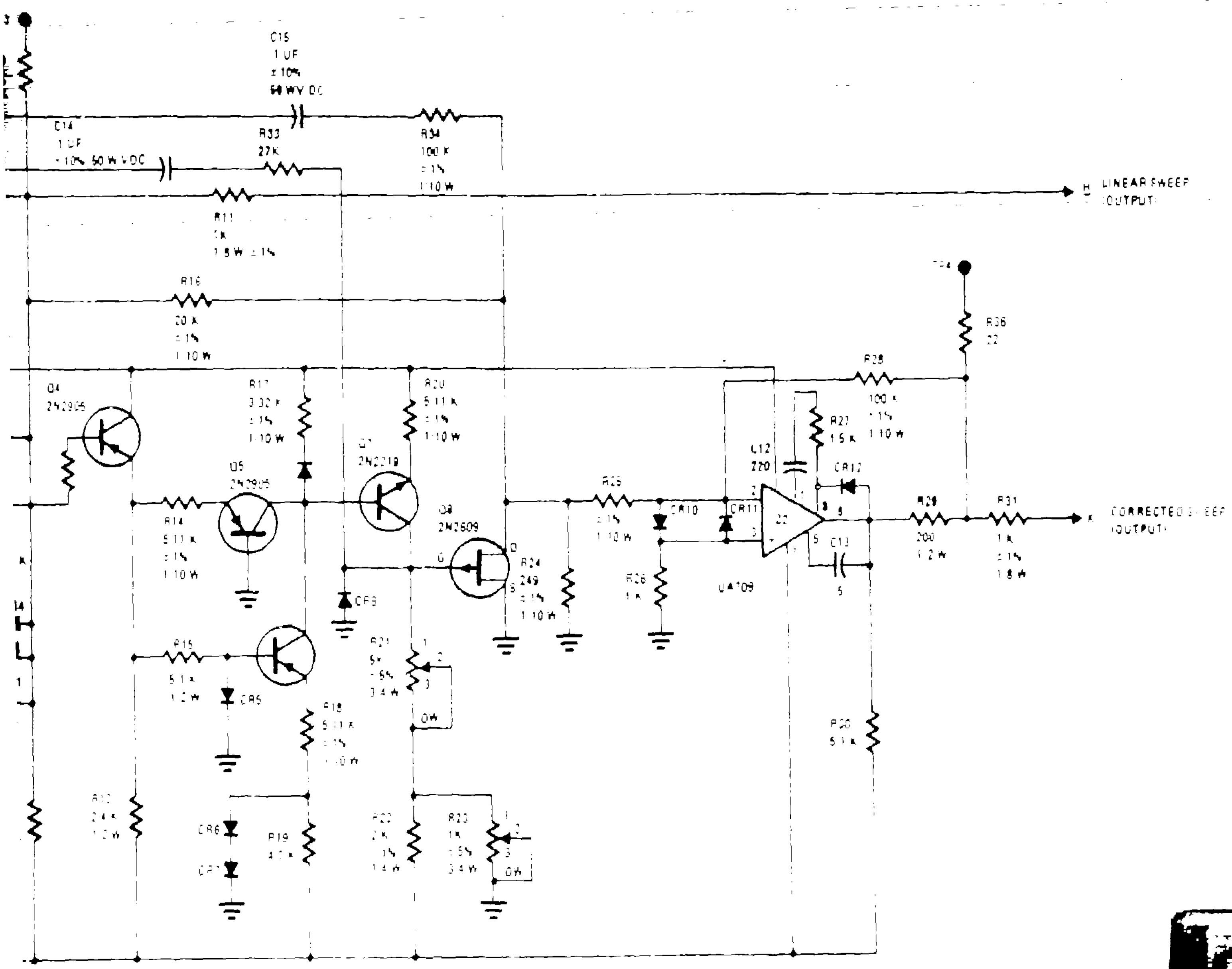
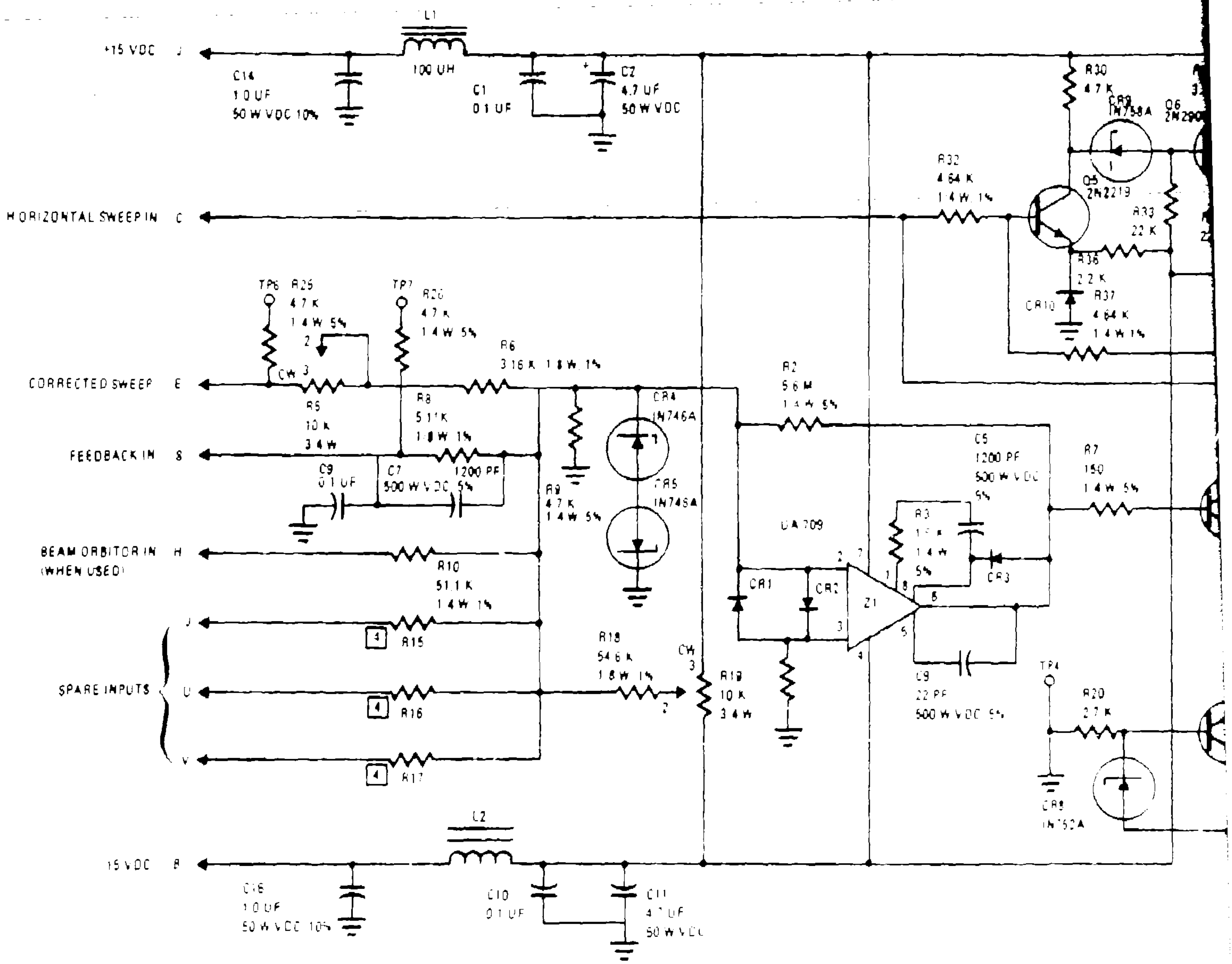


Figure 80 Linearity Corrector and Sweep Generator Circuit Card Schematic



+15 VDC J
HORIZONTAL SWEEP IN C
CORRECTED SWEEP E
FEEDBACK IN 8
BEAM ORBITOR IN H
(WHEN USED)
SPARE INPUTS
15 VDC B
L1
100 UH
C14
1.0 UF
50 W VDC 10%
C1
0.1 UF
C2
4.7 UF
50 W VDC
R30
4.7 K
CR9
1N758A
Q6
2N290
R32
4.64 K
1/4 W 1%
Q5
2N2219
R33
22 K
R36
2.2 K
R37
4.64 K
1/4 W 1%
CR10
TP6
R25
4.7 K
1/4 W 5%
TP7
R26
4.7 K
1/4 W 5%
R6
3.16 K 1/8 W 1%
R5
10 K
3/4 W
R8
5.11 K
1/8 W 1%
C9
0.1 UF
C7
500 W VDC 5%
1200 PF
CR4
1N746A
CR5
1N746A
R9
4.7 K
1/4 W 5%
R2
5.6 M
1/4 W 5%
C5
1200 PF
500 W VDC
5%
R7
150
1/4 W 5%
UA709
R3
1/4 W
5%
CR1
CR2
CR3
Z1
R10
51.1 K
1/4 W 1%
R15
R16
R17
R18
54.6 K
1/8 W 1%
CW
R19
10 K
3/4 W
C9
22 PF
500 W VDC 5%
TP4
R20
2.7 K
CR8
1N752A
L2
C16
1.0 UF
50 W VDC 10%
C10
0.1 UF
C11
4.7 UF
50 W VDC

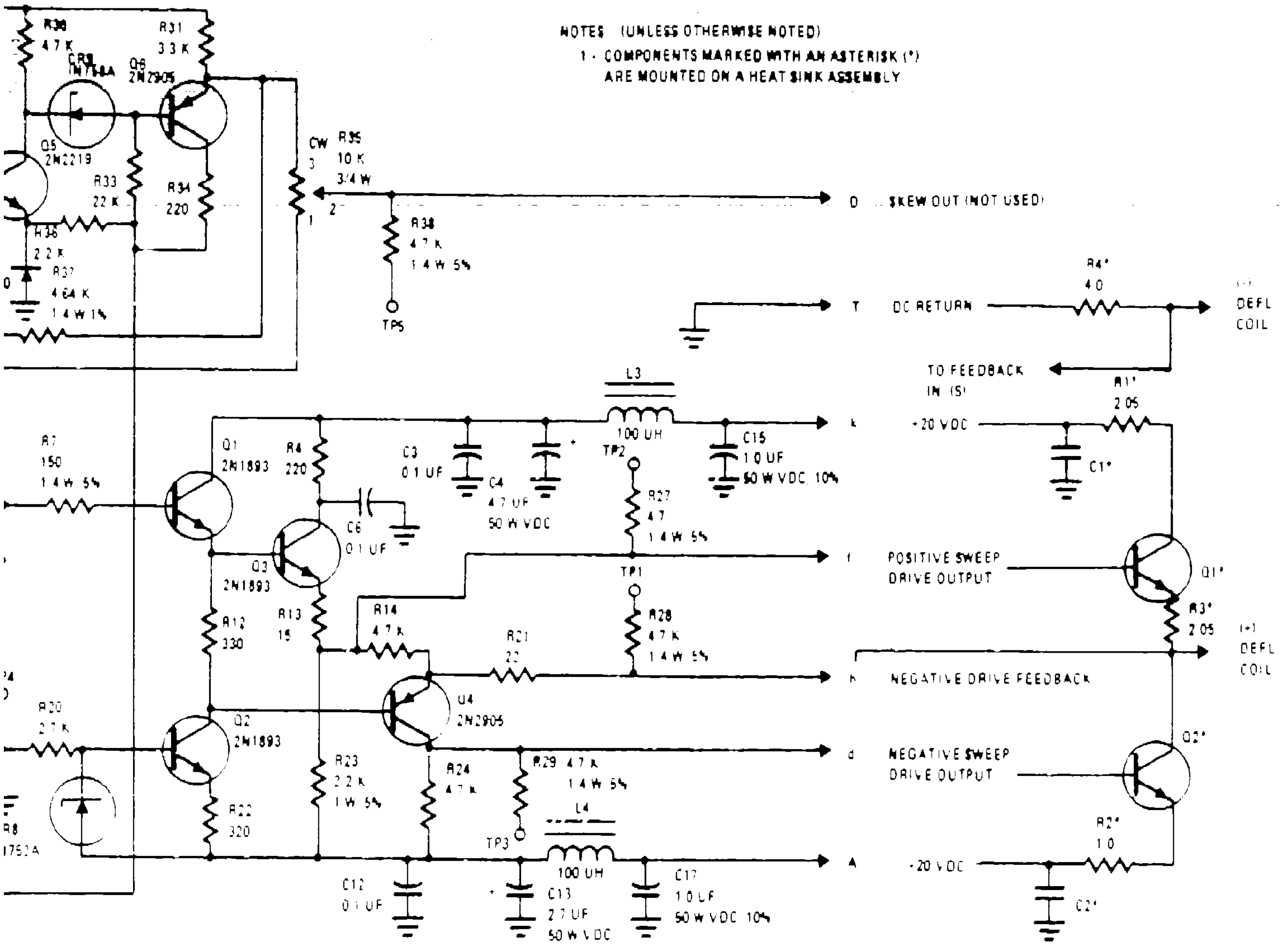


Figure 81 Vertical Deflection Amplifier Circuit Card Schematic

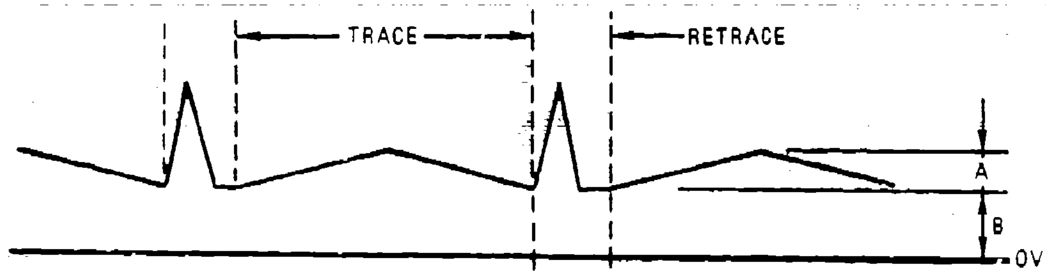


Figure 82 Correction Input to Q8-G

7.3.2 Horizontal Deflection System

The initial circuit implementation was as shown in Figure 83. The concept had been developed at Philco WDL for possible use in commercial color television sets. The initial breadboard was constructed with components designed for use at relatively slow-speed applications to test the feasibility and to provide an insight into the probable limitations for the high-speed circuit. The main benefits of this design are the very low-power requirements combined with very high degree of linearity obtainable. The breadboard operated with less than 35 watts of total power and produced a deflection current adequate for commercial television with a linearity of approximately 2%. However, the disadvantages of this circuit, when scaled up for high-speed operation, are associated with the recovery time of the SCR. The recovery time becomes too short for even the fastest available SCR, and the voltage and current requirements for the semiconductors become the limiting parameters in this application.

The circuit operates as follows. The sync signal input switches the SCR ON to initiate the resonant flyback reset of the yoke. The voltage, due to the charge on the resonating capacitor C in inverted, stepped up, and applied to the deflection yoke through the action of the flyback transformer. The yoke and the capacitor become a resonant circuit and can be represented as shown in Figure 84.

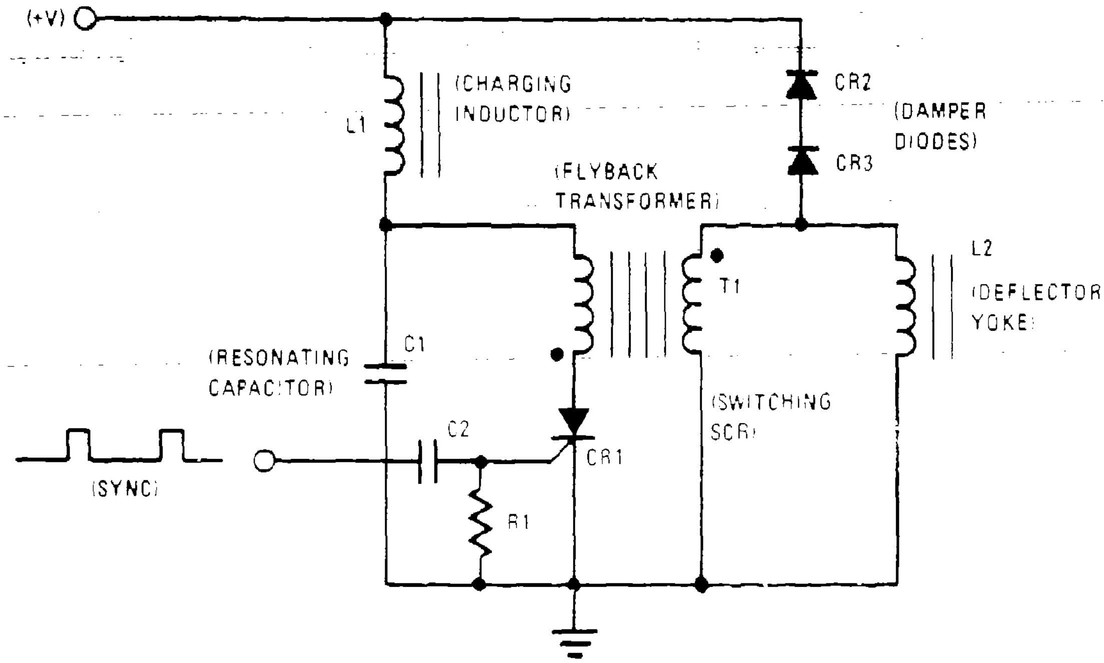
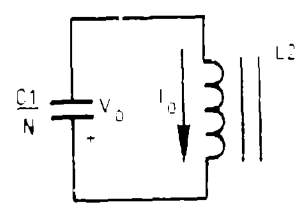


Figure 83 Initial Deflection Circuit



INITIAL CONDITIONS
I_0 = PEAK DEFLECTION CURRENT
$V_0 = (N)(V_{C_1})$

Figure 84 Equivalent Flyback Circuit
(Valid Only During Flyback Period)

This circuit resonates for only one quarter of its resonant period at which time the voltage at the CR_2 - L_2 junction has become positive enough to forward bias CR2 and CR3. The diodes hold the voltage from increasing further. At the same time the current in L_2 has resonated for 1/4 period to a value of approximately - I_o. Thus the resonant action has succeeded in resetting the current in the deflection yoke and the voltage across the deflection yoke has returned to + V + (V_{cr2} + V_{cr3}). During the flyback period the transformer builds up its internal field. Then during the trace period the collapsing field in the transformer holds the deflection yoke voltage constant by keeping CR2 and CR3 forward biased. The voltage on the resonating capacitor influences the voltage on the deflection yoke only during the flyback period.

The operation of the circuit during the trace period can be understood with the use of the equivalent circuit shown in Figure 85. The initial current in the SCR (I_{o1}) is the current required to reset the deflection yoke, multiplied by the transformer turns ratio. This reset current is equal to twice the peak deflection current (the current goes from plus I peak to minus I peak).

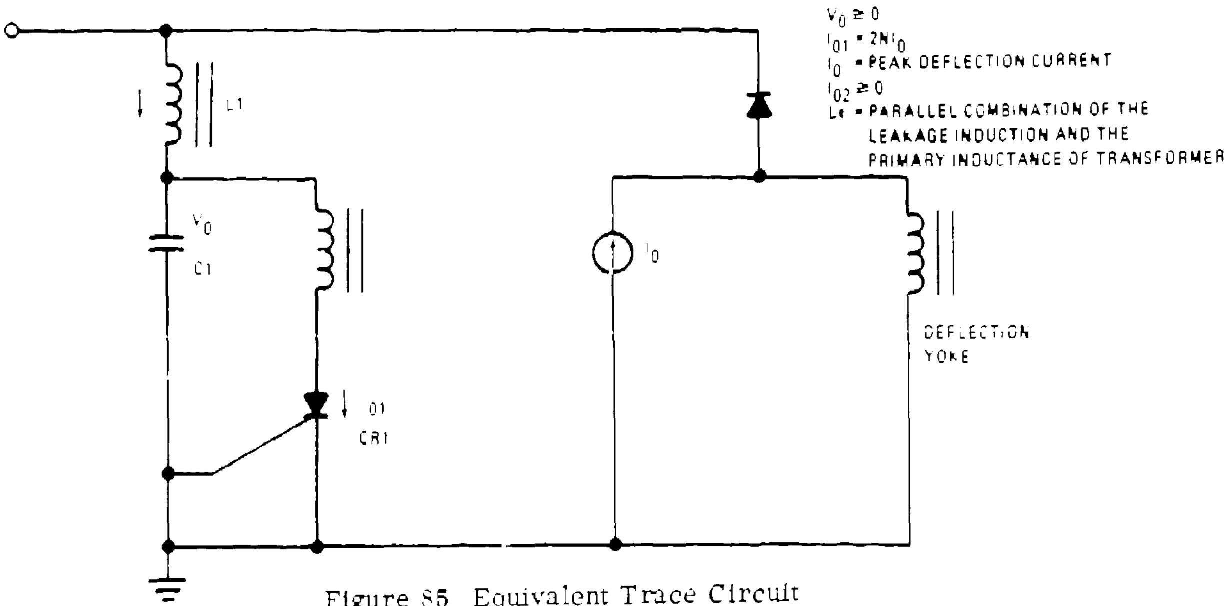


Figure 85 Equivalent Trace Circuit
(Valid Only During Trace Period)

The initial current in L1 (I_{o2}) is small and can be assumed negligible for ease of analizing the circuit. Capacitor C, has resonated from a positive charge to zero during the flyback period and V_o can be assumed zero. Le and C_1 then resonate for 1/4 cycle until the current through CR1 decreases to zero at which point CR1 becomes reversed biased. C1 is

now charged with a negative voltage approximately equal in amplitude to the applied voltage (+V). During this time the current in L1 has increased only slightly because of its relatively long time constant, but, as CR1 becomes reversed biased, Le is removed from the circuit and L_1 and C_1 become a resonant circuit for 1/2 cycle. This returns the charge on C_1 to its initial condition prior to flyback.

Utilizing the same circuit concept, high-speed transistors were substituted for the switching SCR. A new high sensitivity deflection yoke was chosen and the transformer and charging inductor were redesigned. The use of transistors instead of SCR's was a significant change due to the major impact on the complexity of the drive circuits. Using transistors allows a more precise control over switching functions but is troublesome due to more complex control input requirements. The modified design allowed low power operation at the proper frequency (8 μsec trace and 2 μsec retrace) but also taxed the limiting parameters of each component. The first limit was found to be the saturation characteristics of the transformer. Evaluation of the transformer requirements showed that an optimum design would involve a trade off between two main parameters: high secondary inductance and low-leakage inductance. A number of transformers were constructed with different option changes involving core size, core material, winding configuration, and wire construction.

Further developments on the circuit involved using special "state-of-the-art" (high voltage, high current, and high speed simultaneously) transistors for the power switching function and the addition of a feedback loop to provide a free running mode of operation to safeguard the display in the event of loss of input sync. The developments of high-speed, high-voltage semiconductors and a good high-frequency pulse transformer were the major keys to the implementation of the horizontal deflection system. The design of the transformer can be described by referring to the equivalent circuits of Figure 84 and 85 and considering the transformer equivalent circuits in Figures 86, 87, and 88.

It becomes evident from these equivalent circuits that the important parameters are: leakage inductance (Le), secondary inductance (Is), dc current saturation characteristic ($Is \sim D_{dc}$), and the turns ratio (N).

The leakage inductance must be kept at a minimum since it is in series with the output, and the secondary inductance must be maximum since it is in parallel with the output. But these requirements are mutually inconsistant since both are directly proportional to the number

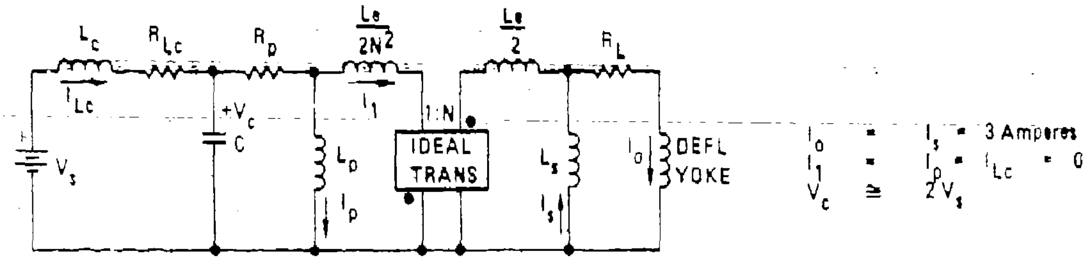


Figure 86 Equivalent Transformer Circuit During Retrace Period

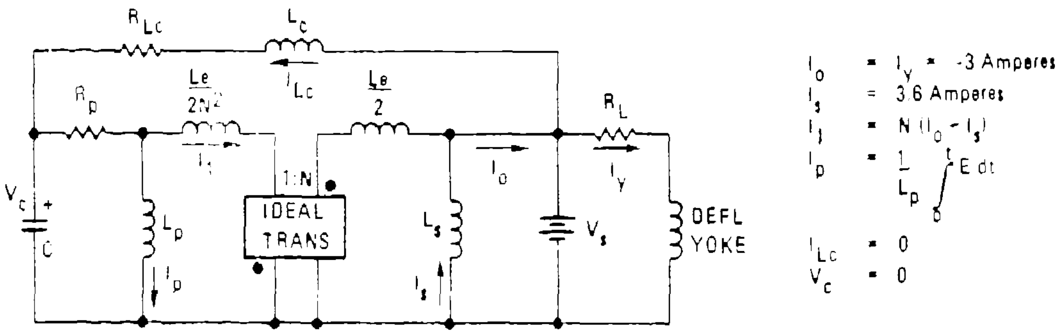


Figure 87 Equivalent Transformer Circuit During First Part of Trace Period

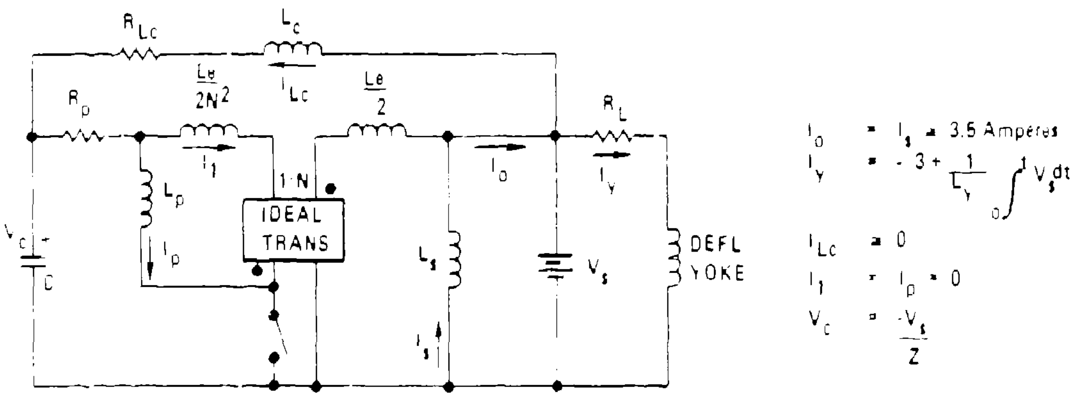


Figure 88 Equivalent Transformer Circuit During Last Part of Trace Period

of turns (n) on the transformer. The saturation characteristic is also directly proportional to n. Using the following design formulas relating these parameters and the core data, a best compromise solution is found as follows:

transformer core air gap $lg = \frac{.5\,nI}{Bdc}$ (inches)

secondary inductance $Ls = \frac{.4\,\pi n^2\,Ac \times 10^{-8}}{le/\mu ac + 2.54\,lg}$ (henries)

leakage inductance $Le = \frac{(31.92)lcun\,(Ts/3 + T_{s-p}) \times 10^{-3}}{W}$ (μ henries)

CORE: Ferroxcube 6656 Part # K5-350-11-3E (core half)

Bobin: P4-564-71

A_L = 18200 mH/1000T μe = 2440

le = 4.84 in = 12.3 cm

A_e = 1.11 in^2 = 7.15 cm^2

V_e = 5.39 in^3 = 88.3 cm^3

Winding area = 0.620 in^2 (Full Bobbin)

Mean length of turn = 5.118 in = 13 cm

$$ig = \frac{(0.5)\,(0.25)\,(3.0)}{2000} = 0.0187'' \cong 0.02''$$

$$Lac = \frac{(1.26)\,(625)\,(7.15)\,10^{-8}}{\frac{12.3}{2500} + (0.02)\,(2.54)} = (1.26)\,(0.12)\,(7.15)\,10^{-5} = 1.0\text{ mH}$$

$$L_e = \frac{(32)\,(4.5)\,(0.625)\,(0.05 + 0.05)}{1.5} = 6\,\mu H$$

The turns ratio is determined by calculating the relationship of the retrace voltage to the trace voltage and then approximating the losses in the circuit that effect the wave shape of the retrace voltage. Under ideal conditions the retrace voltage is the fourth quarter of a sine wave but because there is a rise time associated with the initiation of retrace, and

because there are resistive losses and series impedances between the yoke and the resonating capacitor, it is necessary to make an approximation of the actual voltage wave shape. A good approximation is a triangular wave as shown in Figure 89.

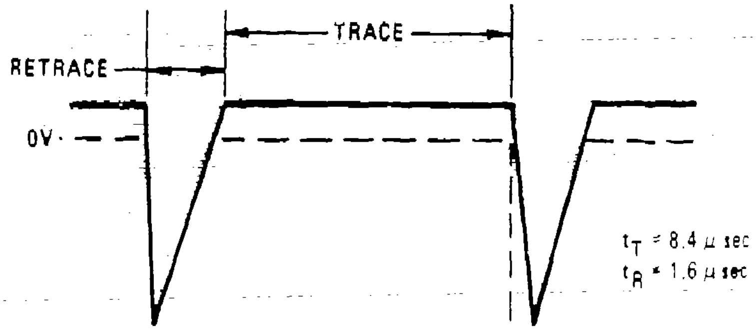


Figure 89 Deflection Yoke Voltage (Approximation)

For zero dc current in the yoke the Vt product must be zero thus.

(trace voltage) (trace time) = (retrace voltage) (retrace time)

$$(V_T)(t_R) = (V_R/2)(t_R) = V_R = \frac{(2)(V_T)(t_T)}{t_R}$$

$$V_R = \frac{(2)(60)(8.4)}{1.6} = 630V$$

turns ratio $N = \frac{630}{120} = 5.2$

with $M = 25$

primary turns $= \frac{25}{5.2} \simeq 5$ turns

Notice also in the preceeding calculations that numbers were used for size and spacing of the windings i.e.: lcu = mean length turn, Ts-p = thickness of insulation between primary and secondary. These numbers were determined by using the winding configuration of Figure 90.

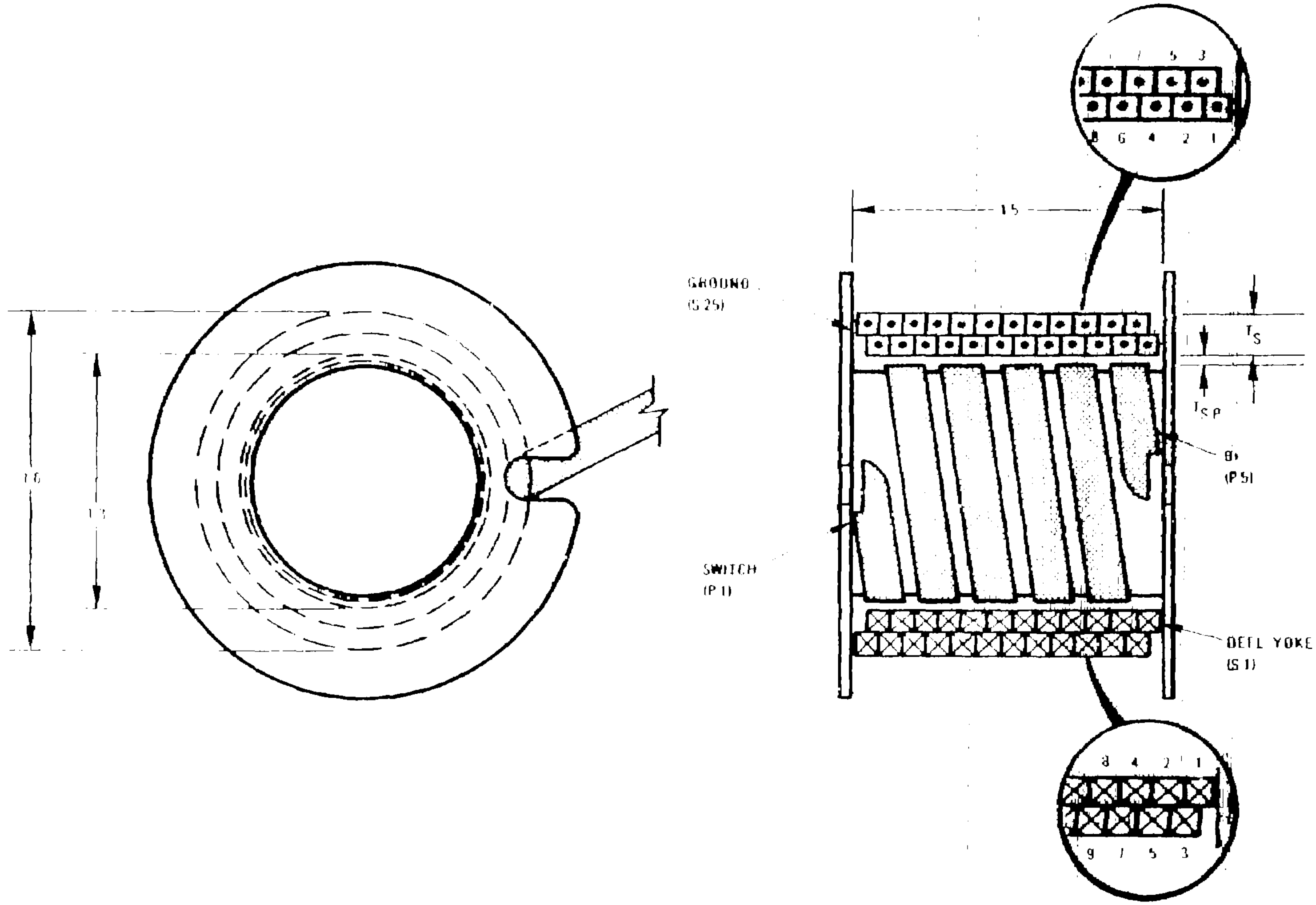


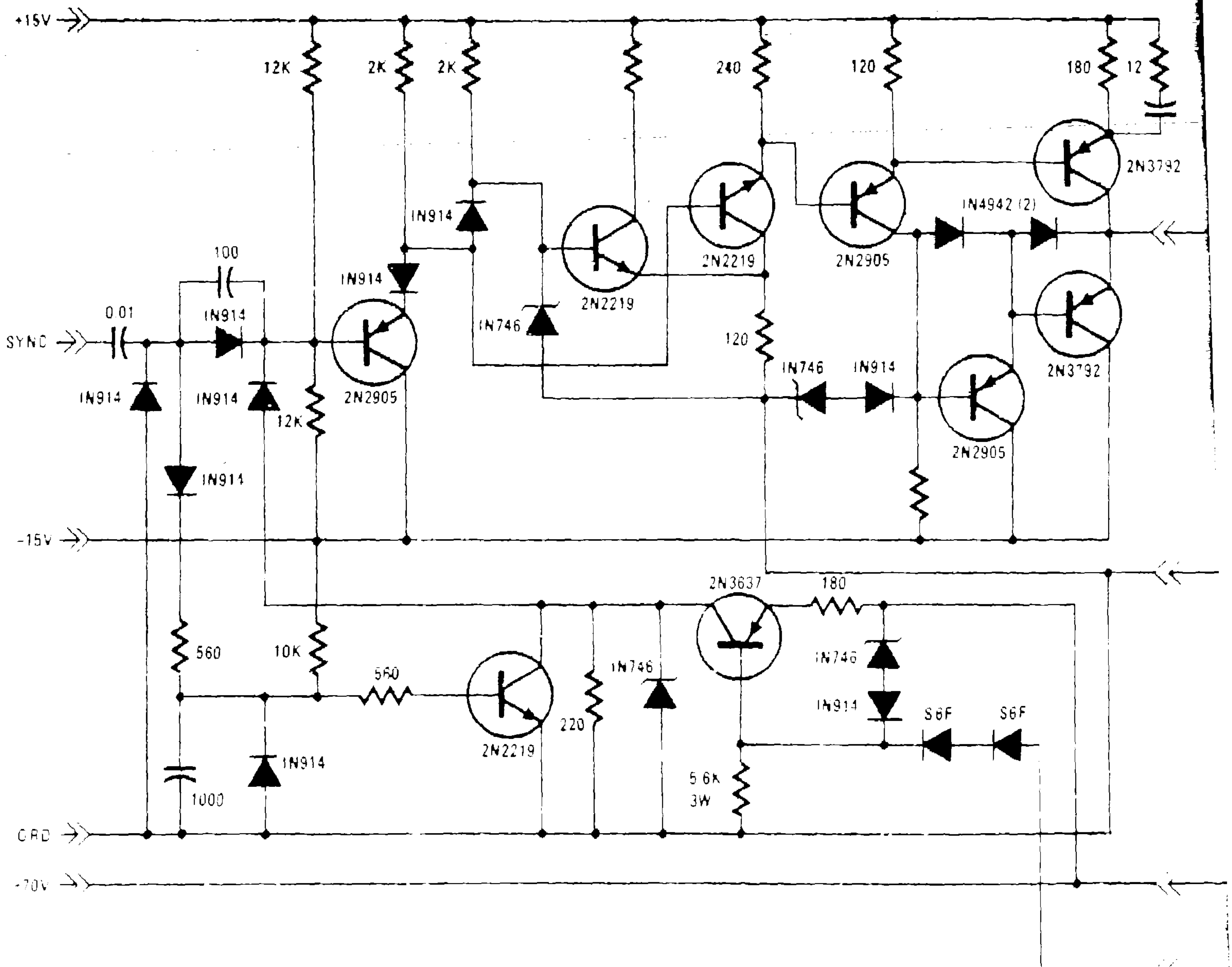
Figure 90 Transformer Construction

The primary windings are made with copper strap 7/32"-wide by 20-mil thick. The secondary windings are made with a Litz type wire consisting of 4 strands of 20 AWG heavy formvar twisted evenly into a cable. A third winding consisting of one turn was put on the transformer to supply a dc voltage to be used for horizontal positioning of the raster of the CRT. This winding does not affect the operation of the other circuitry because it conducts current only during retrace. The present circuit configuration is as shown in Figure 91.

The output circuit operates as previously described except that the switching function is accomplished with transistors. The SVT 250-30 and the two 2N 3846 transistors provide the power switching that was accomplished by the SCR in the slow speed circuit. The SCNAIF and 3SF4 diodes are required by keep from reverse biasing the transistors. The IN3014B zener diode provides over-voltage protection for the transistors which becomes necessary in the event the input sync becomes unstable or erratic. The drive to these transistors is provided by two darlington connected circuits. One for turn-on and the other to turn them off. The "on" circuit is connected as a constant current source to provide isolation between the input and the drive. Enough current is provided through the 180 Ω resistor to keep the output transistors saturated during the retrace period and the 12 Ω-0.047 μF RC combination provides an extra boost to speed up the turn on of these transistors. The OFF circuit is connected as an emmitter-follower to provide a very low impedance that can drain the base charge from the output transistors and turn them off quickly. The two IN4942 diodes keep both circuits from being on at the same time. Two 2N2219 transistors are connected as a non saturating differential amplifier switch to drive the darlington stages, and a 2N2905 provides a high input impedance for the sync signal. The 2N3637 feeds back a signal to retrigger the circuit for the free running mode if there is no sync signal input. This feedback signal is eliminated whenever there is a sync signal by the 2N2219. The 1000 pF capacitor is charged by the input sync which turns on the 2N2219 and shorts out the feedback signal. The discharge time constant is such that the feedback takes over control if more than two sync pulses are missing.

A comparison of the operation of the present circuit to the design goals is made in Table V.

The photographs of Figure 92 show the voltage and current waveforms obtained with 38 kV anode potential and the deflection circuits adjusted for full screen deflection. The current ramp linearity is measured by overlaying a straight line intersecting the end points of the current ramp and measuring the vertical deviation. Measurement of the display linearity


+15V
SYNC
-15V
GRD
-70V
12K
2K
2K
240
120
180
12
2N3792
IN914
IN4942 (2)
2N2219
2N2905
100
0.01
IN914
IN914
IN746
2N2219
120
IN746
IN914
2N3792
IN914
IN914
12K
2N2905
2N2905
IN914
2N3637
180
560
10K
560
IN746
IN746
IN914
S6F
S6F
220
2N2219
IN914
5.6K
3W
1000

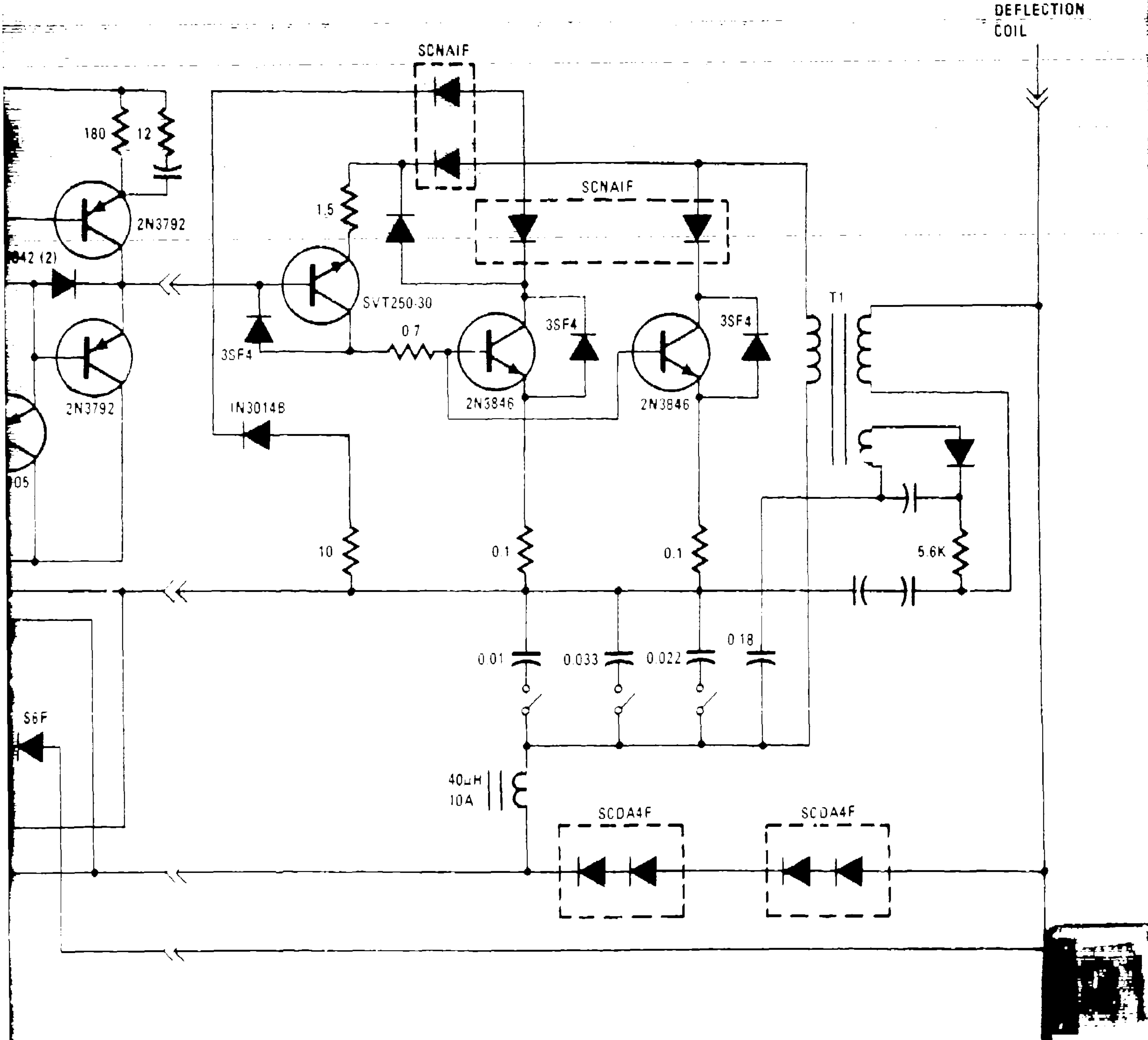
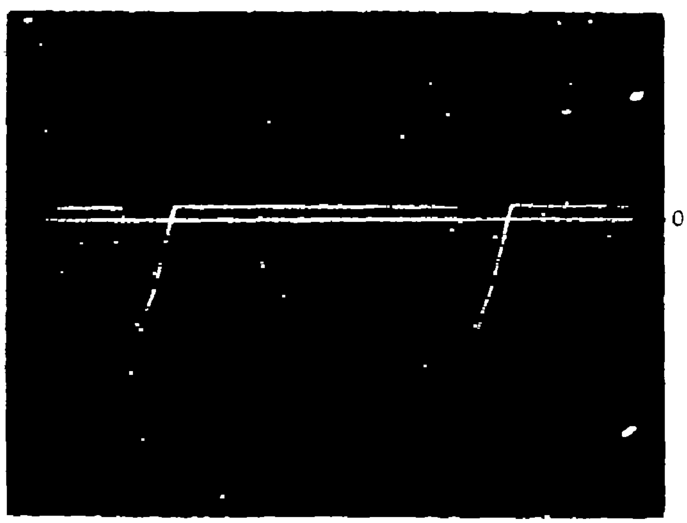


Figure 91 Horizontal Deflection Circuit

VERT: 1.0 AMP/CM HORIZ: 2.0 µS/CM



VERT: 200V/CM HORIZ: 2.0 µS/CM

Figure 92 Deflection Yoke Current and Voltage

TABLE V
COMPARISON OF PRESENT CIRCUIT TO DESIGN GOALS

PARAMETER	DESIGN GOAL	ACTUAL	REMARKS/CONDITIONS
Horizontal period (μs)	9.87	9.0-11.5	Circuit operates at input sync
Trace (μs)	7.9	7.2-9.2	rate within these limits
Retrace (μs)	1.97	1.8-2.3	
Deflection current			Using FYS 448-5600/500 with
(Pk-Pk Amperes)	5.5	5.6	58V Supply.
Raster size (Inches)	3.1 square	3.1 square	5M117 Thomas CRT @38 kV
			Using above yoke with 4.2A p-p
Power Req't	100 watts	110 watts	58V Supply @ 1.7A dc ±15V
			@0.4A
Linearity			
Current ramp	2%	3.5%	Same conditions as for raster
Display (on axis)	2%	3%	size measurement

was made by using a photograph of the projected image of the 512 color bar pattern on the screen. The red-field pattern breaks the screen into 64 equal time intervals by using the edge transition between the brightest and darkest red bar. The distance (to the nearest 0.01 in.) from the left edge to each of these transistions was made and compared to its calculated relative distance for perfect linearity. The deviations were normalized to reflect measurement from center to edge of the display and the linearity was determined as the deviation times 100 divided by the distance from center.

Recommendation - as has been stated, the circuits developed contain unique designs associated with the flyback transformer and the high speed switching transistors. These developments enabled high speed performance with excellent non-corrected linearity of the display and relatively low power dissapation. A further advantage of this method is the elimination of the cross-over distortion present in conventional resonant flyback deflection.

Future improvements would involve a redesign of the magnetics (transformer, deflection yoke) to reduce the power requirement and improve the linearity of the display The major power dissipation is caused by the high currents in the switching transistors and associated diodes which are characterized by fixed voltage drops almost independent of the current.

By increasing the operating voltage of the magnetics, the current requirement decreases in direct proportion. The power requirement is thus reduced, but not without cost. The voltage breakdown requirement of the transistors increases by twice the increase in supply voltage and of the damper diodes by five times the increase in supply voltage.

Other improvements should involve the incorporation of linearity correction methods such as a passive reactance in series with the deflection yoke to create an "S" curve deflection ramp or a negative resistance amplifier in series with the yoke to cancel the resistive losses in the yoke.

SECTION 8

COLOR WHEEL CONTROL SERVO

8.1 COLOR WHEEL DRIVE

The color wheel drive brings the color wheel up to speed and locks the wheel into synchronism with the scanning electron beam. The drive must position the various color filter sections in front of the CRT with the correct phase and speed if good color purity is desired. The design specifications for the drive system are given in Section 8.1. Section 8.2 discusses the alternatives considered and the design which was finally selected. Test results are discussed in 8.3.

8.2 DEISGN SPECIFICATIONS

Synchronous Speed		1800 RPM
Phase jitter		± 15°
Pull-in Torque	estimated	10-15 in-oz.
Pull-out Torque	estimated	10-15 in-oz.
Starting Torque	estimated	10-15 in-oz.

The pull-in, pull-out, and starting torque specifications were estimated from rough calculations of the amount of windage and bearing friction expected for color wheel drive. Some tests were made on a laboratory synchronous motor driving a plastic disk to verify the amount of torque required.

8.3 DESIGN SELECTION

Three different drive schemes were considered for the color wheel drive.

Alternative 1: Synchronous AC motor with phase-locked loop. The first method utilizes a synchronous motor with feedback to a phase-locked loop as shown below in Figure 93. Two position markers at the beginning of each red field generate a position pulse which is compared in the phase detector with the reference sync pulse. Any phase error will generate a correction voltage which changes the frequency of the Voltage-controlled-oscillator (VCO) in a direction which will decrease the phase error to zero. Fine adjustment of the phase is possible either by inserting an error voltage to the VCO or changing the location of the position marker sensor.

Advantages	Disadvantages
automatic phasing	fairly complex circuitry
good phase stability	pull-out torque determined only by motor rather than motor and drive

Alternative 2: Synchronous hysteresis motor with direct drive. A block diagram of the second alternative appears in Figure 94. This system is similar to alternative 1 except that no automatic phase control is provided.

The reference sync pulse in this system is used to drive the color wheel through a pulse reshaping circuit and a power amplifier contained in the drive circuit. Using a synchronous hysteresis motor, the lock-in phase is arbitrary and phase shift circuitry is required to adjust the phase of the color wheel to the correct value.

Advantages	Disadvantages
good phase stability	no automatic phasing
simple	pull-out torque determined by motor only

Automatic phase capability could be incorporated in this system; however, if automatic phasing is desired, alternative 1 might be a better choice.

Alternative 3: DC Motor with phase-locked loop. This system is the most sophisticated of the three alternatives considered and gives the best performance. As shown below in Figure 95, this alternative is a true speed and phase control servo system with excellent position accuracy and speed control. The reference sync pulse is compared in frequency and phase to

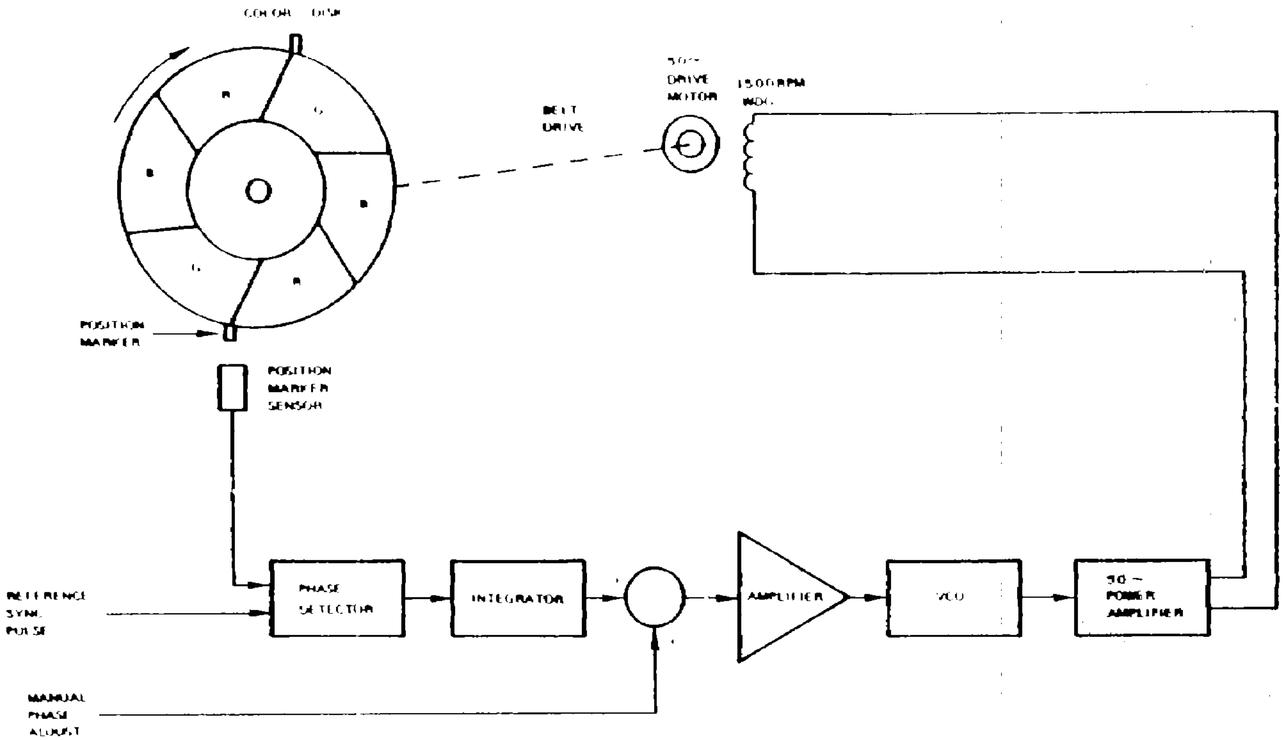


Figure 93 Color Disk Servo, Alternative 1

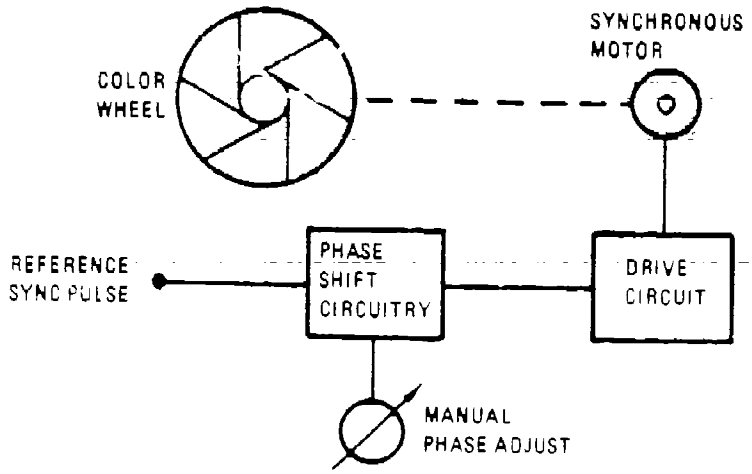


Figure 94 Synchronous Hysteresis Motor with Direct Drive

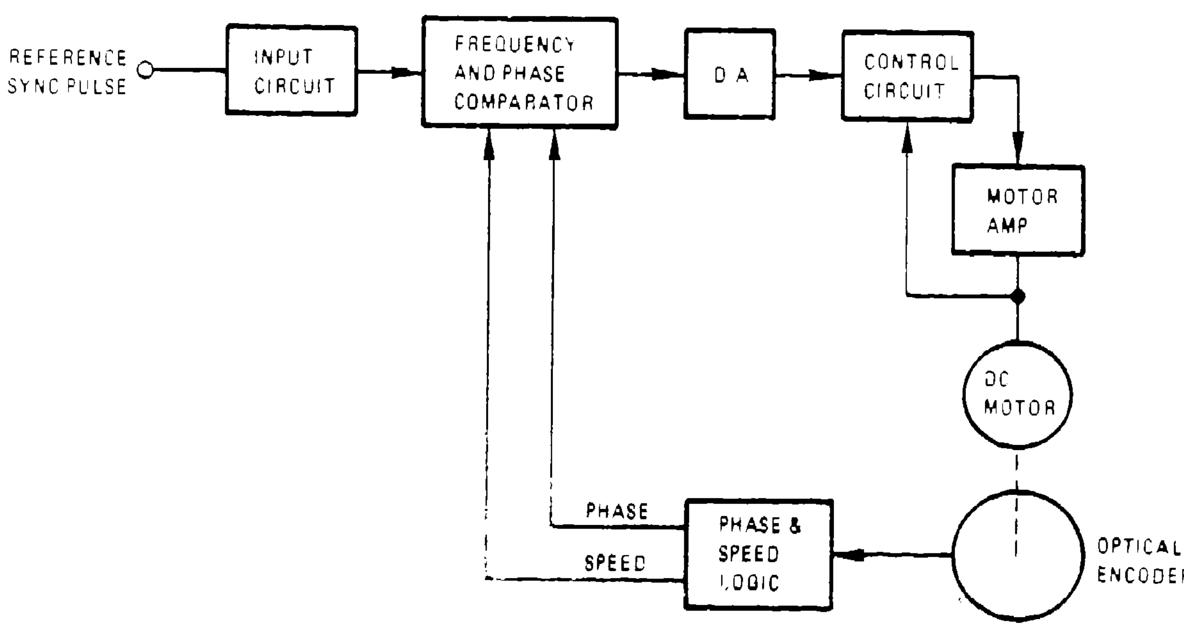


Figure 95 DC Motor with Phase-Locked Loop

the phase and speed signals sent from the optical encoder. At non-synchronous motor speeds only a logical frequency error signal is developed to bring the motor up to speed. After synchronism is achieved, the phase error is then nulled out. Commercial servo systems using this approach have attained instantaneous position accuracy of better than ±10 arc seconds and are very insenitive to load variations because of the broad band high gain feedback.

Advantages	Disadvantages
excellent phase stability	high cost and complexity
high torque and high stiffness for small motor size	
insenitive to load variations	

Design Tradeoffs and Selection of Experimental Design. For use in an airborne application where high G forces may be encountered, alternative 3 is the best choice since the varying bearing and gyroscopic loads on the color wheel motor will not affect the wheel speed or phasing.

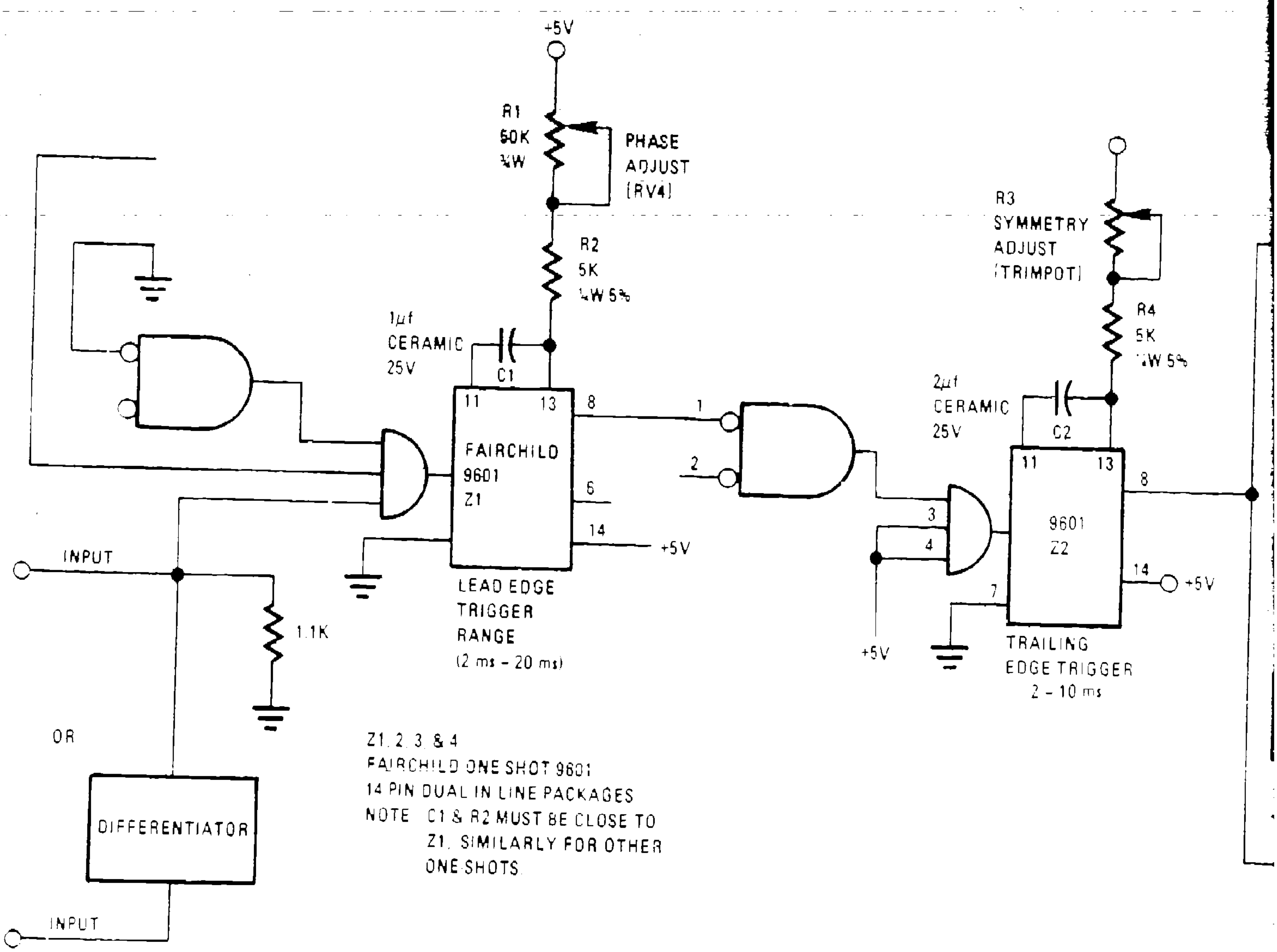
Alternate 1 and 2 are essentially the same except for the automatic phasing.

For the purposes of the study and the experimental display, the simplest approach, that of alternative 2 was chosen for implementation. The schematic and details of operation follow in Section 8.4.

8.4 DESCRIPTION OF DRIVE SYSTEM AND SCHEMATIC

Figure 96 is a schematic of the color wheel servo.

The one-shot Z1 is a Fairchild 9601 integrated circuit device which is connected to trigger on the leading edge of the red field pulse as shown in the Timing Diagram (Figure 97). The timing of Z1 is variable by means of the "Color Wheel Phasing" potentiometer which is located on the front panel of the display. The range of adjustment of Z1 is from 2 milliseconds to 20 milliseconds to allow any of the red, green, or blue filter segments of the color wheel to be phased to the proper position regardless of the phase obtained when the color wheel


+5V
R1
50K
¼W
PHASE
ADJUST
(RV4)
R2
5K
¼W 5%
1μf
CERAMIC
25V
C1
FAIRCHILD
9601
Z1
LEAD EDGE
TRIGGER
RANGE
(2 ms – 20 ms)
INPUT
1.1K
OR
DIFFERENTIATOR
INPUT
R3
SYMMETRY
ADJUST
(TRIMPOT)
R4
5K
¼W 5%
2μf
CERAMIC
25V
C2
9601
Z2
+5V
TRAILING
EDGE TRIGGER
2 – 10 ms
Z1, 2, 3 & 4
FAIRCHILD ONE SHOT 9601
14 PIN DUAL IN LINE PACKAGES
NOTE C1 & R2 MUST BE CLOSE TO
Z1. SIMILARLY FOR OTHER
ONE SHOTS.

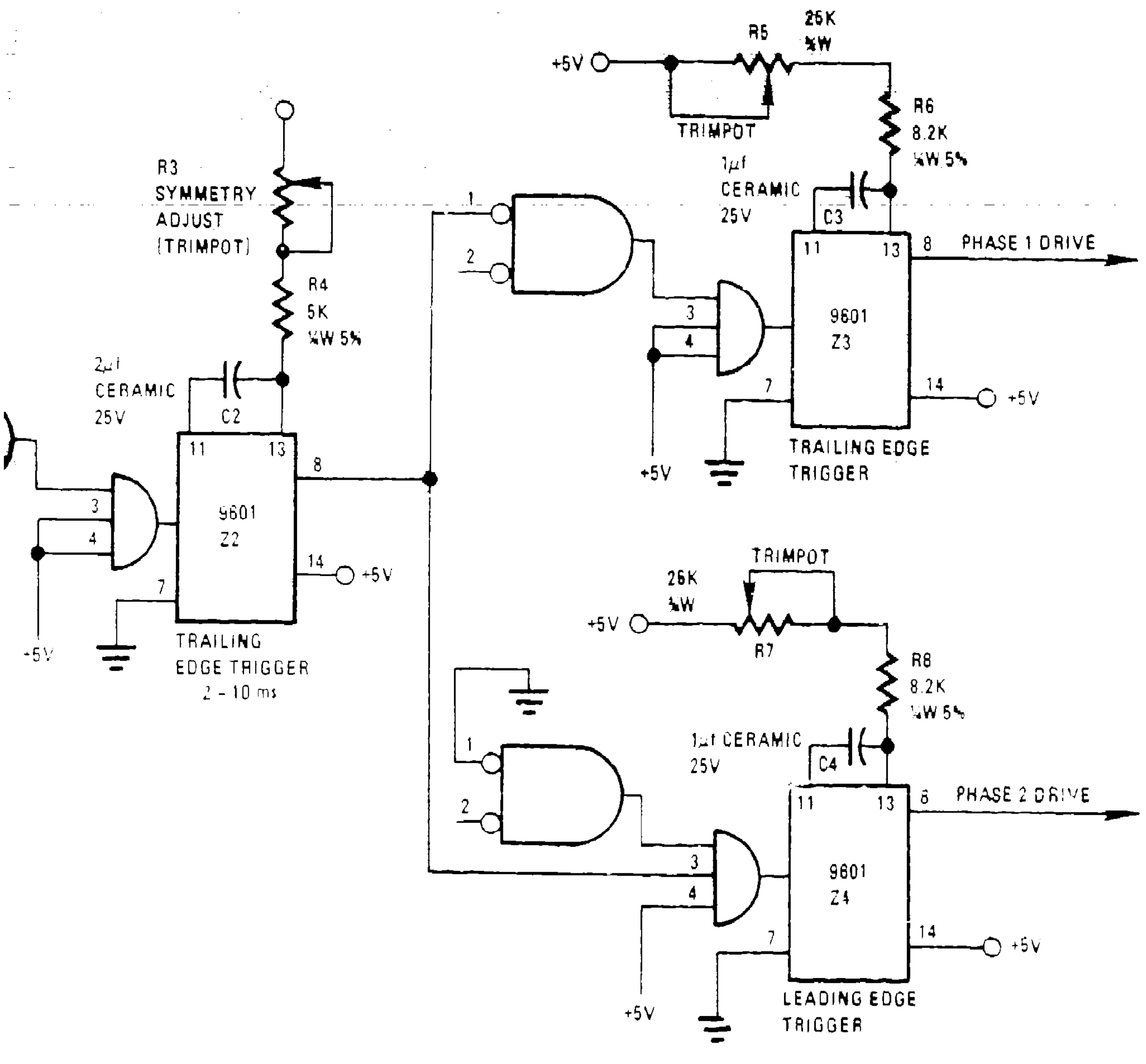


Figure 96A Color Wheel Servo

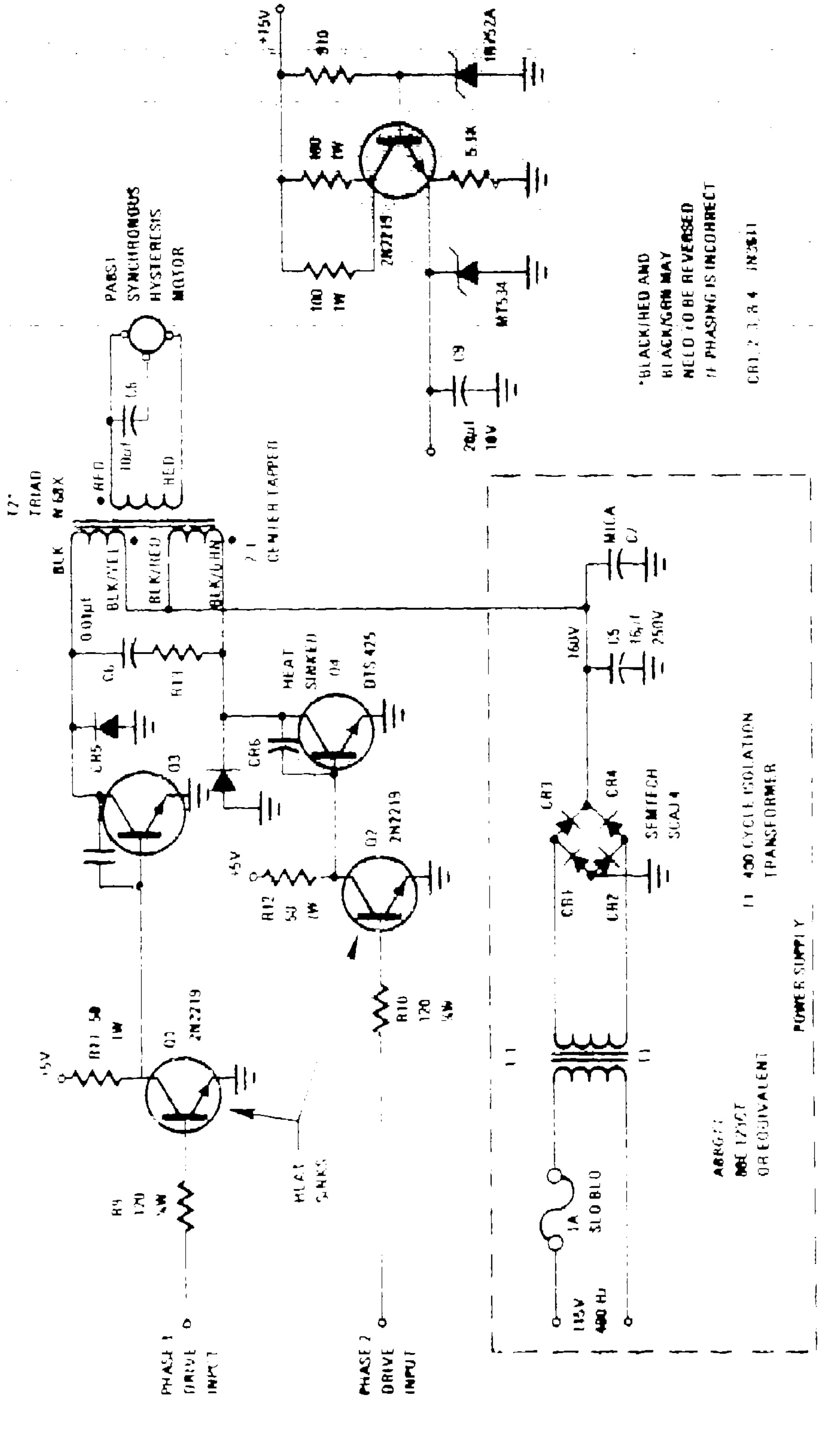


Figure 96B Color Wheel Servo

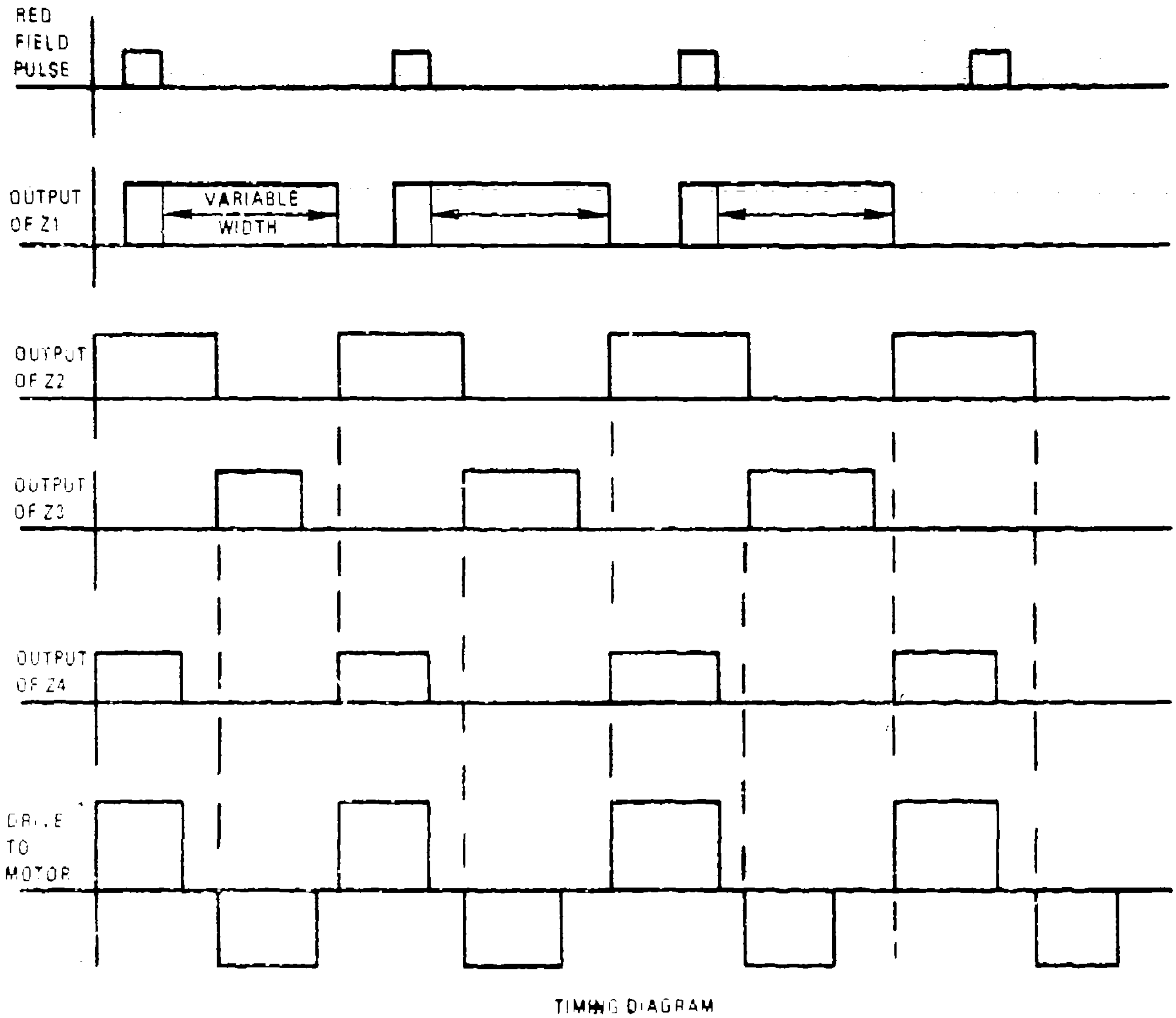


Figure 97 Timing Diagram

first locks up to the drive frequency. It is characteristics of the synchronous hysteresis motor to lock in synchronism at an undetermined phase position.

Z2 is triggered by the trailing edge of the pulse from Z1. The width of this pulse is adjusted to be exactly one half the period of the red field pulses by means of the symmetry adjust trimpot R3, located on the color wheel drive circuit card. The output of Z2 is thus a square wave which can be moved in phase with respect to the input red field pulses.

Z3 is trailing edge triggered by the output of Z2; and Z4 is leading edge triggered by Z2 to develop two symmetrical drive signals to the transistors driving the power transformer T2.

The two drivers turn on alternately to develop the voltage needed to operate the motor. Since the drive signals are synchronous with the red field pulses and the color wheel is synchronous with the drive, the color wheel stays in phase with the field information.

A few of the significant details of the circuitry (See schematic Figures 96A and 96B) are as follows. The diodes CR5 and CR6 are included to prevent the collector base junctions of the DTS 425 power transistors from being forward biased when the opposite transistor turns on. The damping network consisting of R13 and C6 is necessary to control the transients caused by the Q_3 and Q_4 turn-on and turn-off. C7 is a high frequency capacitor to prevent oscillation of Q_3 and Q_4. T2 is a special design to handle the square wave input drive without saturating. This transformer was designed by TRANEX, Mountain View, Ca. The synchronous hysteresis motor is an external rotor design with sleeve bearings. The external rotor design of this motor yields high torque and small size, and the sleeve bearings give quiet operation with a minimum of vibration.

5.5 TEST RESULTS FOR COLOR WHEEL DRIVE SYSTEM

The completed color wheel drive system operates satisfactorily in the Real Time Improved Color Display. The color wheel is driven through a right angle crossed helical gear system which generates a small amount of noise due to a slight hunting of the color wheel.

Test Results

Synchronous Speed	1500 to 1800 RPM
Phase Jitter	± 10° approx.
Starting Torque	19 in-oz.
Pull-in Torque	est. ~19 in-oz.
Pull-out Torque	est. ~ 19 in-oz.
Time to Achieve Phase-Lock from Rest (1500 RPM)	25 seconds

Drive System Data

- Color Wheel

Size of Color wheel	0.240" x 12 1/4" diameter
Material	Pyrex glass
Weight of color wheel	2 lbs. 4.5 oz.
Moment of inertia of wheel	~1.72 oz-in-sec^2

- Drive Motor

Type	External Rotor, Synchronous hysteresis
Size	3 1/4" diameter x 2 1/4" long
Speed	1500 to 1800 RPM
Input Power	~60 watts
Moment of inertia of rotor	~0.2 oz-in-sec^2

As an approximation, the gear and windage torque losses may be calculated as the difference between the starting torque (T_s) and the torque required (T_r) to bring the color wheel up to 1500 RPM in 25 seconds. For a thin disk with no damping:

$$J_o \alpha(t) = T_r$$

and $J_o \int_o^{t_o} \alpha(t)\, dt = \int_o^{t_o} T_r\, dt$

or $J_o W(t_o) = T_r t_o$

$$T_r = \frac{J_o W(t_o)}{t_o}$$

where

$J_o = J_{o\,motor} + J_o$ color wheel

$= 0.2 + 1.72$ oz-in-sec^2

$$T_r = \frac{1.92 \text{ oz-in-sec}^2}{25 \text{ sec}} \; \frac{50 \text{ rad}}{\text{sec}}$$

$$W(t_o) = \frac{1500 \text{ RPM } 2\pi \text{ radians}}{60 \text{ sec}}$$

$T_r = 12.05$ oz-in

$= 50\pi \;\frac{\text{radians}}{\text{sec}}$

$t_o = 25$ sec

$T_s = 19$ oz-in

$T_s - T_r = 6.95 \cong 7$ oz-in

Thus, for the laboratory system about 7 oz-in of the available motor torque is necessary to counteract the bearing, gear and windage losses. Any motor supplying more than 7 oz-in of torque could bring the color wheel up to speed although the time to achieve synchronism would be excessively long if the torque is near 7 oz-in. Also, the stiffness and resulting phase-stability of the color wheel would be poor.

The present motor is a Pabst HSM 20.65-4-95D. This motor was selected because of its high torque external rotor design and its low cost. For an adverse environment application, a sealed internal rotor motor could be selected if further analysis of the load disturbances showed that a synchronous hysteresis motor could be utilized while maintaining the required phase stability. In general, the size and weight of a synchronous hysteresis motor with sufficient torque for this application would be appreciably greater than that of a small DC servo motor of the same capability.

8.6 CONCLUSIONS AND AREAS FOR FURTHER STUDY

Control of the color wheel is a fairly simple servo problem. For ground applications, where no random load distrubances occur, a simple open end drive using a synchronous motor yields excellent performance. For airborne applications, the lack of stiffness of the synchronous motor approach will probably cause unacceptable oscillation of the color wheel about the correct phase position.

8.6.1 Conclusions

a. For ground applications, use synchronous motor with automatic phasing.

b. For airborne application, use a dc servo system with velocity and position feedback to attain high resistance to load disturbances while maintaining light weight and small size. The tradeoff is the much greater circuit complexity of the dc servo system compared to the synchronous motor system.

8.6.2 Areas for Further Study

Two areas should be investigated further with respect to the possible implementation of a sequential display in airborne applications. These are:

a. A literature search and investigation of the G-forces and pitch and yaw rates for various aircraft.

b. A program to determine analytically and experimentally the load disturbances on the color wheel drive system due to the aircraft maneuvers investigated in part A.

Both of these areas are fairly simple to study and would firmly establish the specifications for a color wheel servo for aircraft use.

SECTION 9

HUMAN FACTORS CONSIDERATIONS

9.1 INTRODUCTION

Human Factors considerations are of great importance in assessing the Real Time Improved Image Display. The match of human operator visual characteristics and the corresponding design aspects of the display must be known in order to determine the best utility of this device. The relevance of color as an information display technique has been frequently discussed in the literature and Human Factors design criteria for color displays have been devised for most ordinary applications [1, 2, 3]. In addition, visual criteria influencing the design of color CRT display systems have been widely investigated[4].

In this report, a Human Factors evaluation of the design parameters for this specific display device is presented. The most important of these parameters (color generation method, resolution and registration) are examined in greater detail and recommendations are made for additional studies which must be performed to define more clearly the applications in which this device can be most effectively used.

9.2 PHYSICAL DESIGN CHARACTERISTICS AND PSYCHOLOGICAL CORRELATES

The physical design characteristics of the Tri-Color Display were identified in the original specifications and engineering tests have been performed for these design parameters (see Section 1.4 of this report). Psychological correlates which can be identified for these parameters are shown in Table VI. Although the last item in the table, "Color Generation Method" is not a design parameter against which tests were made, it is nonetheless a design characteristics inherent in the device which requires separate treatment from a Human Factors standpoint.

TABLE VI

DESIGN CHARACTERISTICS AND PSYCHOLOGICAL CORRELATES

Design Characteristics	Psychological Correlate
Spatial Frequency Response	Resolution
White Brightness Color Brightness Color Brightness Shades Gray Scale Shading Black and White Contrast Ratio	Brightness
Color Gamut Color Linearity	Hue
Purity	Saturation
Color Misregistration	Registration
Flicker	Flicker
Color Generation Method	Color Hue Perception Method

In the paragraphs which follow, the most relevant of the design characteristics for each of the psychological correlates are discussed.

9.3 RESOLUTION

The measurements of spatial frequency response described in Section 2.1.1 indicate that 1000 lines are resolvable in horizontal and vertical directions. It can therefore be inferred that each element of a digital video raster of 10^6 picture elements will be resolvable from adjacent elements.

As Luxenberg and Kuehn[5] describe, Rayleigh's criterion for the resolution of two point images requires that the center of the diffraction pattern of one point fall on the first dark ring of the other. In achieving this relationship, the minimum illuminance midway between

the two images is 26.5 percent below the two maxima. Actual observations supported by some theory indicate that a differential of 2.2 percent between the maximum and minimum is sufficient for resolving two points. This relationship is known as Conrady's criterion.

Spatial frequency response for displayed lines may be obtained by measuring the maximum illuminance at the center of a line and comparing it against an adjacent minimum in the space between lines. The point resolution criteria described above are applicable to these measurements.

The data indicate a horizontal frequency response of 45 percent and a vertical response of 50 percent, both measured at 1000 lines. These measurements are well within either Conrady's or Rayleigh's criteria for resolution.

9.4 BRIGHTNESS

A maximum of 33 footlamberts of white light was measured for this device.

As is noted in Section 4.0, brightness can be improved by increasing the accelerating voltage any by reducing the green purity. For Command and Control applications, a screen 10 inches by 10 inches is considered suitable for viewing. If this change is implemented; a side benefit would be in the considerable light output improvement.

Measurements of the "Shading" parameter indicate that corner brightness is generally one-half of center brightness. In the photopic luminance range of vision, hue is dependent upon luminance; an effect known as the Bezold-Brucke phenomenon[6]. An apparent shift of 10 to 20 nanometers may be experienced for some colors as retinal illuminance changes. Corrective circuitry can be employed to provide uniform luminance across the display surface.

Section 2.1.3 presented a detailed discussion of gradual brightness fall-off from the center to the edge. This fall-off was not objectionable to an observer. Observation of the image on the laboratory test bed verifies this fact. Before circuitry to correct for this phenomena is utilized, consideration as to brightness loss should be made.

Color brightness shade tests indicate a maximum of 7 shades of red, 12 of green and 5 of blue, where each successive level is $\sqrt{2}$ times greater than the previous level. However, perceived color brightness is not a geometric function of illuminance. Therefore, a quantizing function based upon empirical investigations of distinguishable brightness levels for each primary should be employed rather than the geometric function expressed above.

9.5 HUE

The color gamut measurements indicate that the red and blue primaries lie well within the triangle formed by the NTSC primaries on the CIE Chromaticity diagram and the green primary is slightly displaced from NTSC green.

The hues measured on the three color components are very good when considering available phosphors. Only minor limitations would result and would only be apparent when the display is compared to the original object field.

9.6 SATURATION

As indicated above, the red and blue primaries lie within the CIE NTSC color triangle. Thus, the most pure red on this device will be less saturated than NTSC red and the most pure blue will be less saturated than NTSC blue. The most pure green will be somewhat more saturated than NTSC green.

9.7 REGISTRATION

Virtually no misregistration was detected for this device. Generation of target images can be performed without concern for image recognition and interpretation problems which arise in other systems. The implications of this characteristic, combined with high resolution, are discussed in paragraph 9.10.

9.8 FLICKER

No flicker was detected for the red and blue fields when they were displayed alone. Some flicker was evident for the green field and for the combination of all three fields yielding white when large areas were observed at high screen brightness. However, the frame rate

for this version of the display was only 25 Hz as opposed to the design goal of 30 Hz. The detectability of flicker is substantially decreased at this higher rate, particularly for the retinal illumination achievable with this display[7]. Individual differences in the detection of flicker and in the tolerance of it when it is detected are quite pronounced. For use of this device in an operational environment, display frame rate can be modified to operate at 30 Hz.

9.9 COLOR HUE PERCEPTION METHOD

The perception of the color of an image is a complex phenomenon dependent upon several variables, such as wavelength, illuminance, area of illumination, purity, past experience of observer, luster of surface of object, etc. There are two perceptual mechanisms which are of importance in assessing this display:

a. Perceived color images generated by field sequential color stimuli.

b. Perceived color images formed by the fusion of adjacent image elements having different amounts of primary color components.

These mechanisms are interactive. The former effect governs for large image areas of a single hue, and the latter effect contributes to perceived color of images containing fine detail. The human factors implications of these image formation methods are discussed in the next paragraph.

9.10 ANALYSIS OF CRITICAL HUMAN FACTORS PARAMETERS

In order to perform further analysis of this device from a human factors standpoint, it is first necessary to examine the potential applications, which include the following:

- Display dynamic color images of data obtained in real time directly from a sensor.

- Display stored dynamic data which has been obtained from such sensors.

- Target detection and identification

- Image enhancement and analysis by employing digital techniques to encode data for display.

There are three characteristics of this device which warrant further analysis in assessing the suitability of this device to these applications. As indicated in the preceding section, these are:

- Color Hue perception method
- High resolution
- Perfect registration

The generation of color stimuli by means of a rotating color wheel placed between the observer and the display device was the method by which color television was first attempted. It was dropped for commercial color television applications because of lack of compatibility with monochrome systems and decreased definition. These drawbacks are not applicable to the Tri-Color display. However, there is a characteristic of this device which might provide a limitation on the display's application. As Zworykin and Morton point out, "... [An] annoying defect also is fundamental to the system, namely, color fringing and color breakup. If an object moves very rapidly in the picture, its image shows leading and trailing color fringes since the successive color images are displaced so far that they are no longer in register. For a similar reason, if the observer's eye moves rapidly, the successive color fields will not be in register at the retina of the eye, and an unpleasant sensation of bright color flashes is experienced."[8] Since both of these defects involve the same perceptual phenomenon (retinal image misregistration) they will be referred to as the "color breakup" characteristic.

Color breakup will affect the following tasks to which Tri-color could be applied:

a. Interpretation of dynamic images, in which either the sensor or targets move rapidly.

b. Detection and interpretation of transitory phenomena, the duration of which are shorter than the period required for generation of the three successive primary color fields.

c. Identification of targets which appear in a portion of the displayed image far from the current fixation point.

Regarding this last item, reference can be made to OSA's, The Science of Color, "Most chromatic colors appear to change color with change in position, that is, the sensation may change from strong red to weak yellow to pure gray, or from green to yellow to gray, during slow movement of the stimulus from the fovea to the periphery. ...Thus, most chromatic stimuli, if greatly reduced in size or luminance, fail to elicit chromatic color sensations anywhere in the peripheral retina..."[9]. It can be inferred that if an observer is viewing a screen of constant hue and a target should appear in his peripheral vision, the color of the target will tend to be shifted toward the color of the last field that is presented on the screen as the observer shifts his fixation point to the target. This coloration will result from the retentive characteristics of the retina (which permits the integration of successive fields to yield perceived hues) and the initial homochromatic after image. However, the more serious problem is the color breakup of the target image as the eye shifts from the fixation point to the target. A series of target images, each of a separate color component, will be perceived as the eye moves and fixates on the target. ...However, our informal observations indicate that the affects of the breakup phenomenon are substantially reduced as the frame rate is increased.

High resolution combined with nearly perfect registration is commonplace in displayed data (i.e., printed or photographic material). However, this combination gives rise to the perception of color by a second process, which is the fusion of adjacent colors of different hues. If the image contains fine detail near the resolution limits of the device, then it is likely that the perceived image will be an additive mixture of the components of the image. Ralph M. Evans in An Introduction to Color describes the phenomenon qualitatively as follows: "When small colored areas are far enough away so that individual areas cannot be seen, it is impossible to tell whether the color seen is continuous. The color would look exactly the same if all the small areas were replaced with a single large area having the mixture color. ...For example, a random series of red and green dots covering a surface will be seen as such if the dots can be resolved by the eye, and no trace of yellow will be visible. As the distance from the observer increases, there will be a point at which the mixture color comes and goes (usually as a yellowish brown since a bright yellow cannot be produced in this manner) and red, green, and brown are all visible at once. At greater distances the color becomes permanently brown and cannot be seen in any other way." And later, "Distant viewing of small colored areas may fuse them to an entirely new color. Finally, viewing of surfaces from an intermediate distance may make their appearance fluctuate between the color of individual areas and the fusion of the whole"[10].

If perceived hue is to be used as a recognition parameter for images containing fine detail, the scheme used for encoding the data for display must take into account this perceptual characteristic.

9.11 RECOMMENDED ADDITIONAL STUDIES

As the preceding sections of this report demonstrate, there are some perceptual effects of the Tri-Color Display for which insufficient data exists to make Human Factors conclusions. This data can only be obtained by performing studies in which empirical data is gathered from observers who view the display under controlled conditions. These studies are required to determine the functions and the operational conditions for which this display is best suited. Four study areas have been identified which are of importance in defining the role of this device in display technology. Brief descriptions of these studies are given below.

9.12 BREAKUP PHENOMENON

Image color breakup will occur for both digitally generated and analog generated displays. For digitally generated displays every point in a moving image can be generated in each color field; however, in analog displays, movement of rapidly moving objects will result in the leading and trailing edges of the image appearing in only one or two of the color fields at any given instant. Breakup for digitally generated displays will result primarily from movement of the eye fixation point; however, for analog displays both eye movement and rapid object movement will contribute to image misregistration on the retina.

9.12.1 Purpose of Study

The purpose of this study is to determine the rates of image target motion at which breakup occurs and to determine the degree to which breakup interferes with perception of the target. Investigations will be made for both analog and digitally generated data.

9.12.2 Experimental Method

The method of limits will be employed in this study, using bars which move across the screen at controlled rates. The dependent variable will be movement rate; independent variables will include bar color, background color, bar width and luminance.

9.12.3 Stimulus Generator

The stimulus generator for the digitally generated displays must be a memory system capable of generating images of bars in each color field and moving them across the display surface. For analog displays, a pulse generator having pulse width, height and phasing controls will be required.

9.13 COLOR PERCEIVED BY FUSION OF ADJACENT ELEMENTS

9.13.1 Purpose

The purpose of this study is to determine display resolution at which fusion contributes to the perception of color hue.

9.13.2 Experimental Method

The method of limits will be employed using picture element matrices of various resolutions. The dependent variable will be detection of fusion; independent variables will be matrix resolution, matrix color, brightness and screen viewing distance.

9.13.3 Stimulus Generator

A digital memory will be required which is capable of generating dot matrices in various patterns, such as those shown below.

RGBRGBRGB...	RRGGBBRR...
GBRGBRGBR	RRGGBBRR...
BRGBRGBRG	GGBBRRGG...
RGBRGBRGB	GGBBRRGG...
.	.
.	.
.	.

9.14 COLOR OF PERIPHERAL TARGETS

9.14.1 Purpose

The purpose of this study is to determine coloration of peripheral targets due to retinal retention of last color field when fixation point shifts to peripheral target.

9.14.2 Experimental Method

The method of constant stimulus differences will be employed. A screen of constant hue which contains a fixation target must be provided. A target will be introduced in the periphery and the observers will report hue perceived at the onset of the stimulus. The dependent variable will be perceived color. Independent variables will be target color, screen color, brightness and distance of fixation point from peripheral target.

9.14.3 Stimulus Generator

A digital memory which is capable of generating a static fixation target and permitting the addition of a peripheral target at a given point in time will be required.

9.15 HUE OF TRANSITORY TARGETS

9.15.1 Purpose

The purpose of this study will be to determine the hue of targets displayed on the screen for very brief periods of time. The minimum duration of target stimulus required to match a constant stimulus color will be obtained.

9.15.2 Experimental Method

This study will use the method of constant stimuli using targets which are presented for very brief controlled intervals. The dependent variable will be perceived hue. Independent variables will be target duration, target size, background color, target color, and brightness.

9.15.3 Stimulus Generator

A digital memory capable of generating targets of various sizes, which are presented to the observer at fixed points in time and for controlled durations will be required.

9.16 CITED REFERENCES

1. McCormick, Ernest J., Human Factors Engineering, 3rd., McGraw-Hill, New York, 1970, pp 103-107.

2. Morgan, Cook, Chapanis, Lund, (eds.), Human Engineering Guide to Equipment Design, McGrow-Hill, New York, 1963, pp 81-84.

3. Woodson, W.E., and Conover, D.W., Human Engineering Guide for Equipment Designers, University of California Press, Berkeley, 1964, pp 2-208 through 2-218.

4. Bingley, F.J., "Color Vision and Colorimetry" in Television Engineering Handbook, 1st Ed., D.G. Fink, ed., McGraw Hill, N.Y., 1957, pp 4-1 through 4-45.

5. Luxenberg, H.R., and Kuehn, R.L., (eds.), Display Systems Engineering, McGraw-Hill, N.Y., 1968, pp 150-156.

6. Luxenberg, H.R., and Kuehn, R.L., op. cit., pp. 104-106.

7. Walsh, J.W.T., Photometry, Constable & Co., London, 1958, pp 70-71.

8. Zworykin and Morton, Television, The Electronics of Image Transmission in Color and Monochrome (2nd Ed.), Wiley & Sons, N.Y., 1954, pp 778.

9. Committee on Colorimetry, Optical Society of America, The Science of Color, Thomas Y. Cromwell, N.Y., 1953, pp. 103.

10. Evans, R.M., An Introduction To Color, Wiley, N.Y., 1948, pp 86-87.

SECTION 10

INTERFACE AND SCAN CONVERSION

10.1 BACKGROUND

It must be recognized that the color display has an enormous capacity for information. In one frame alone, 9,000,000 bits of information are consumed (each primary has 8 levels). A sophisticated memory and refresh system is required to present data to the display. In addition, the information may come from numerous devices or sensors. A brief description of sensor or information storage devices is presented. This will serve as background information to help understand the problems faced in designing an adequate interface. Next, the description of the 9,000,000 bit mass memory designed and built to drive and refresh the display will be described.

10.2 SENSING DEVICES

Laser Scanners. Several techniques have been developed for application in laser scanners. Some use galvanometer, repetitive movement while others depend on constantly rotating members such as rotating polygons. A galvanometer driven system would find application in an aircraft environment. The usual mode would be to provide scanning in a direction perpendicular to the flight path while the aircrafts's motion would cause the completion of the scene. The low-frequency characteristics of a galvanometer device would dictate a line scan period not less than several milliseconds. The speed of aircraft would not warrant a faster scan system. A scene generated from such a display would be satisfactory as a moving window display, where the stored information would be updated at each completion of a laser scan.

In order to be displayed, the information on each line would be put in storage and refreshed at an output rate commensurate with the color display sweep period. It is assumed that the period of the laser line scan is in the order of 20 milliseconds, the same information is to

be displayed in 8 μsec at a video bandwidth of 60 MHz. This infers that the required bandwidth of the laser video signal need not be over the order of $BW = \frac{60(8)}{0.020} = 24$ kHz. This rate is well within existing state of the art, A/D conversion techniques.

This bandwidth assumes that there will be a 1-for-1 relationship between a horizontal scan on the display with one scan of the ground. For image recognition, an expansion or magnification is usually desired. An enlargement of 10 to 100 could take place and still be in an accepted input video rate of 2.4 MHz. Linearity and deflection rate errors would begin to significantly affect the reproduced image unless electromechanical compensation were applied.

Although the slow scan is applicable in real time aircraft applications, a secondary conversion may be more desirable, such as conversion from film to raster. Here, a high speed laser scanner would find application. Rotating systems would replace the galvanometer driven type. These laser scanners are within the existing state-of-the-art. The laser spot sweep rate to match the display rate, is still not within the capability of trade, however. These scanners would operate by scanning a film transparency. The transmitted light density is related to the sweep for position. A photo detector senses the transmitted light and a video signal is formed. An apparatus that scanned sequentially as in the test bed, would offer the best interface device.

LLLTV and TV Cameras. Although the targets are of different intensities compared to conventional television cameras, the output signals and scanning rates are essentially the same. Signal to noise considerations limit the upper limit line rate that can be used in a camera of sequential mode. Investigations into utilization of sequential cameras indicated that a present upper limit would be near 600 lines resolution at the field rate of color display. Camera tubes are such that the video signal suffers from small signal to noise properties near this rate. Thus a sequential camera system does not exist to directly interface with the display.

10.3 INFORMATION RECORDING

Magnetic Tape. The recording of video signals on magnetic tape requires more than just an extension of the techniques used in audio recording. The high-frequency limit of a magnetic tape recorder is a function of the head gap and the tape speed. With a practical head gap, the high frequencies of TV signals necessitate high tape speeds.

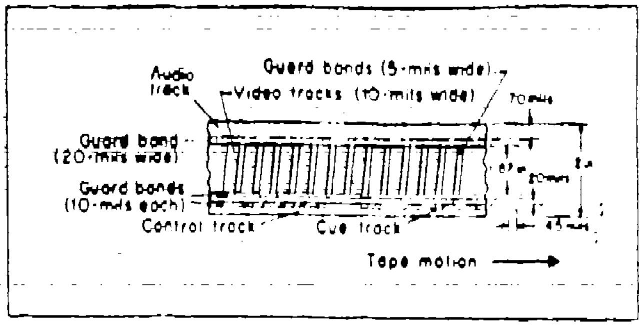
To solve this problem of high tape speeds, Ampex, in 1956, developed a technique known as transverse scanning.[1] With this approach, 2-in wide tape is moved past the record/playback heads at either 15 or 7-1/2 in/s. The record/playback head, however, is actually four heads mounted on a revolving drum. The drum rotates at virtually a 90° angle to the path of the tape. This technique produces an effective head-to-tape speed of about 1,500 in/s and allows recording of frequencies of up to 5 MHz.

Helical scan recorders also use a head (or heads) mounted on a rotating drum. In this case, however, the drum rotates in the same direction as the tape, which is wrapped diagonally around the drum. The video information is recorded as a series of diagonal tracks, with each track containing one TV frame. The helical scan recorders do not have the bandwidth capability of transverse recorders.

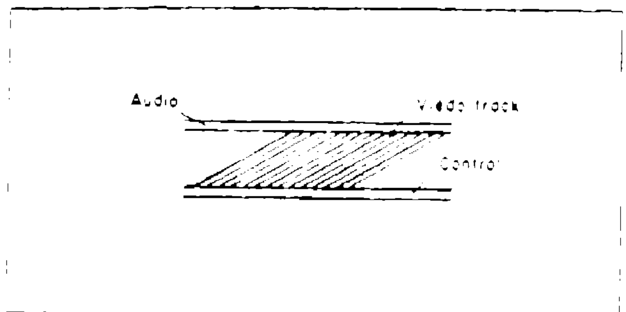
Arvin Industries has experimented with a longitudinal recording system. This corresponds to audio recording, where the tape is moved past stationary heads. Even with a tape speed of 100 in/s, however, the frequency response is only about 1.5 MHz. This means a rather severe limitation on picture quality and a high tape consumption.

Figure 98 depicts the various magnetic tape concepts described above.

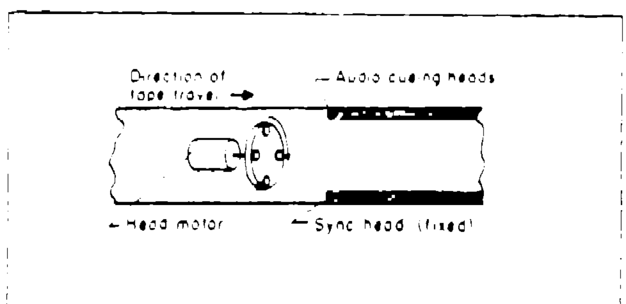
[1] The Electronic Engineer, February 1971.



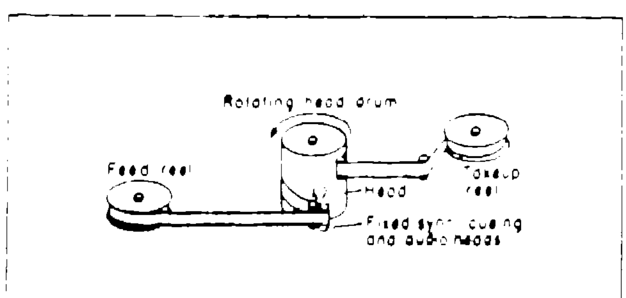
Transverse scanned tape.



Helical scanned tape.



Transverse scan recording.



Helical scan recording.

Figure 98 Magnetic Tape Recording Methods*

*The Electronic Engineer, February 1971

Video Discs. Storing video information on discs is not a revolutionary development. As early as 1927, J. L. Baird successfully recorded a video signal on a 78-rpm phonograph record. The recorded signal, however, had a bandwidth of only 5 kHz.[2]

Teldec (English) and A.E.G.-Telefunken (German) have demonstrated a system for recording video signals on discs which produces quite acceptable black-and-white TV pictures. They also promise that by the time the system becomes available commercially in 1972, it will have color capability.

The system, known as Video Disc, uses either 7- or 12-in. flat discs which give 5-12 min. playing time. The discs resemble phonograph records with two very noticeable differences. Made of 1-mm thick pvc plastic, the grooves of the record attain a density 10 times that of a standard phonograph record. The system has a 2 MHz video bandwidth or about 250 lines of horizontal resolution--about average for a home TV receiver.

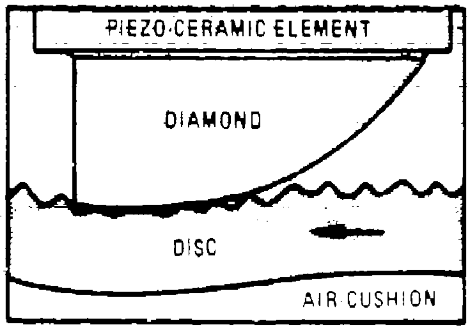
The signal is stored as a hill-and-dale modulation on the top ridges as opposed to the lateral (or side-to-side) modulation in ordinary recording. To overcome the problem of inertia in the pickup at these high frequencies, the system uses a diamond stylus attached to a piezoceramic pressure transducer. Instead of sensing motion, the pickup senses minute pressure variations as the pickup travels over the ridge.

During playback, the stylus does not use the groove walls to track across the disc. Instead, the directly driven pickup arm moves exactly one groove during one revolution of the disc. This technique allows very small tracking forces (0.02 g) promising long record life. Figure 99 depicts the video disc recording method.

How can these devices be used as successful interfaces with the color display? To help realize a satisfactory solution, a large capacity refresh memory must be discussed.

---

[2] The Electronic Engineer, February 1971



The pickup shown here is the secret to playing back video signals from the disc. The diamond stylus flattens the high spots on the disc. When a high spot reaches the trailing edge of the stylus, it springs back to its original shape. This generates a minute shock wave which is sensed by the piezo-ceramic element and converted into an electrical signal.

Figure 99 Video Disk Recording*

10.4 MASS MEMORY REFRESH SYSTEMS

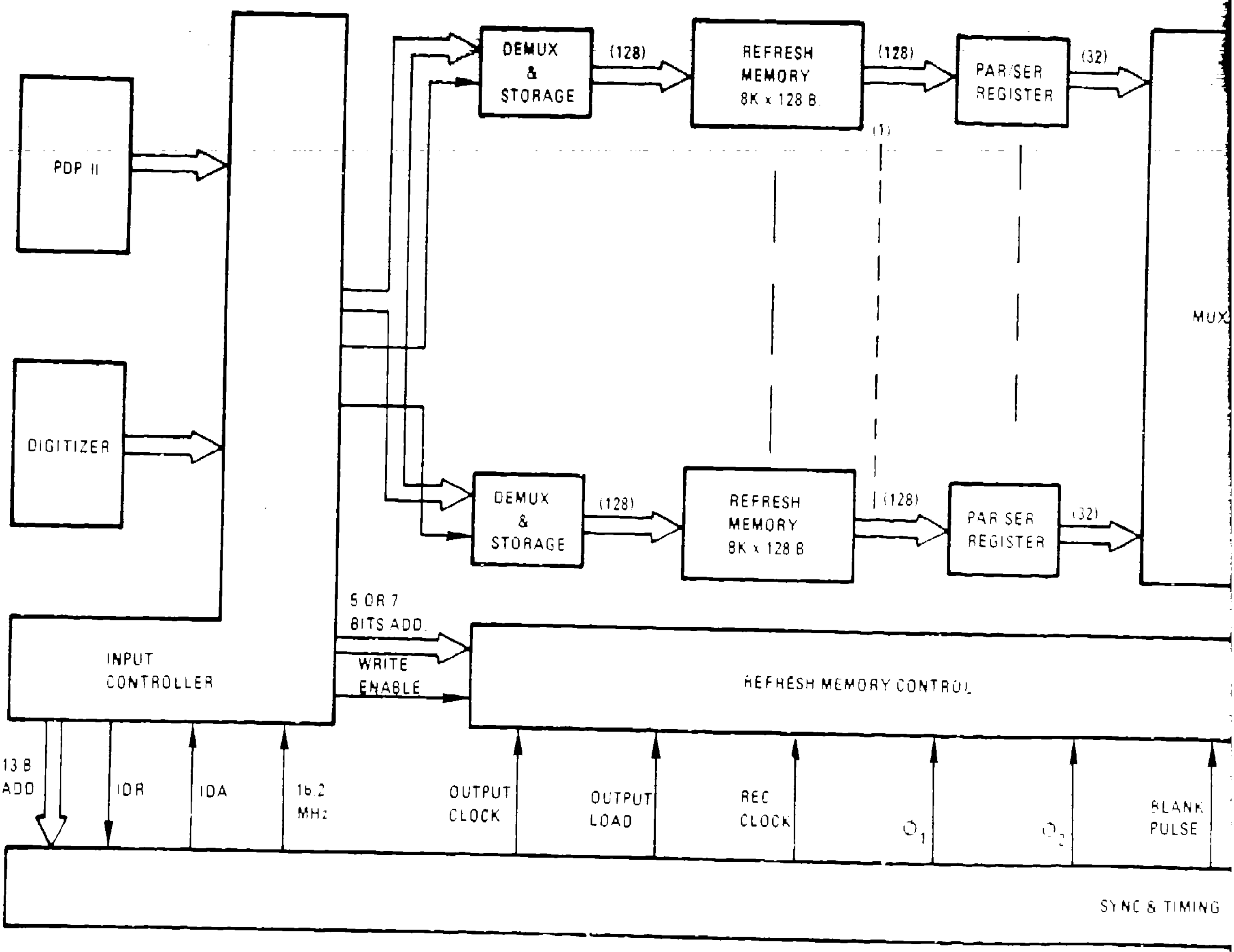
Philco-Ford has designed and fabricated a 9,000,000 bit MOS refresh memory complete with output serializers and computer interface.

As described in Section 6.0, the display system requires a serial data bit rate of 259.2 MHz to maintain a 1024 x 1000 visible lines non-interlaced field with a refresh rate of 3 x 60 = 180 fields per second.

Provisions are also made to operate the system at a bit rate of 129.6 MHz to maintain a 1024 x 500 visible lines interlaced field with a refresh rate of 3 x 60 = 180 fields per second.

Figure 100 shows a block diagram of the mass memory and interface system.

*The Electronic Engineer, February 1971



PDP 11
DIGITIZER
DEMUX & STORAGE
(128)
REFRESH MEMORY 8K x 128 B.
(128)
PAR/SER REGISTER
(32)
(1)
DEMUX & STORAGE
(128)
REFRESH MEMORY 8K x 128 B
(128)
PAR/SER REGISTER
(32)
MUX
5 OR 7 BITS ADD.
WRITE ENABLE
INPUT CONTROLLER
REFRESH MEMORY CONTROL
13 B ADD
IDR
IDA
16.2 MHz
OUTPUT CLOCK
OUTPUT LOAD
REC CLOCK
Φ_1
Φ_2
BLANK PULSE
SYNC & TIMING

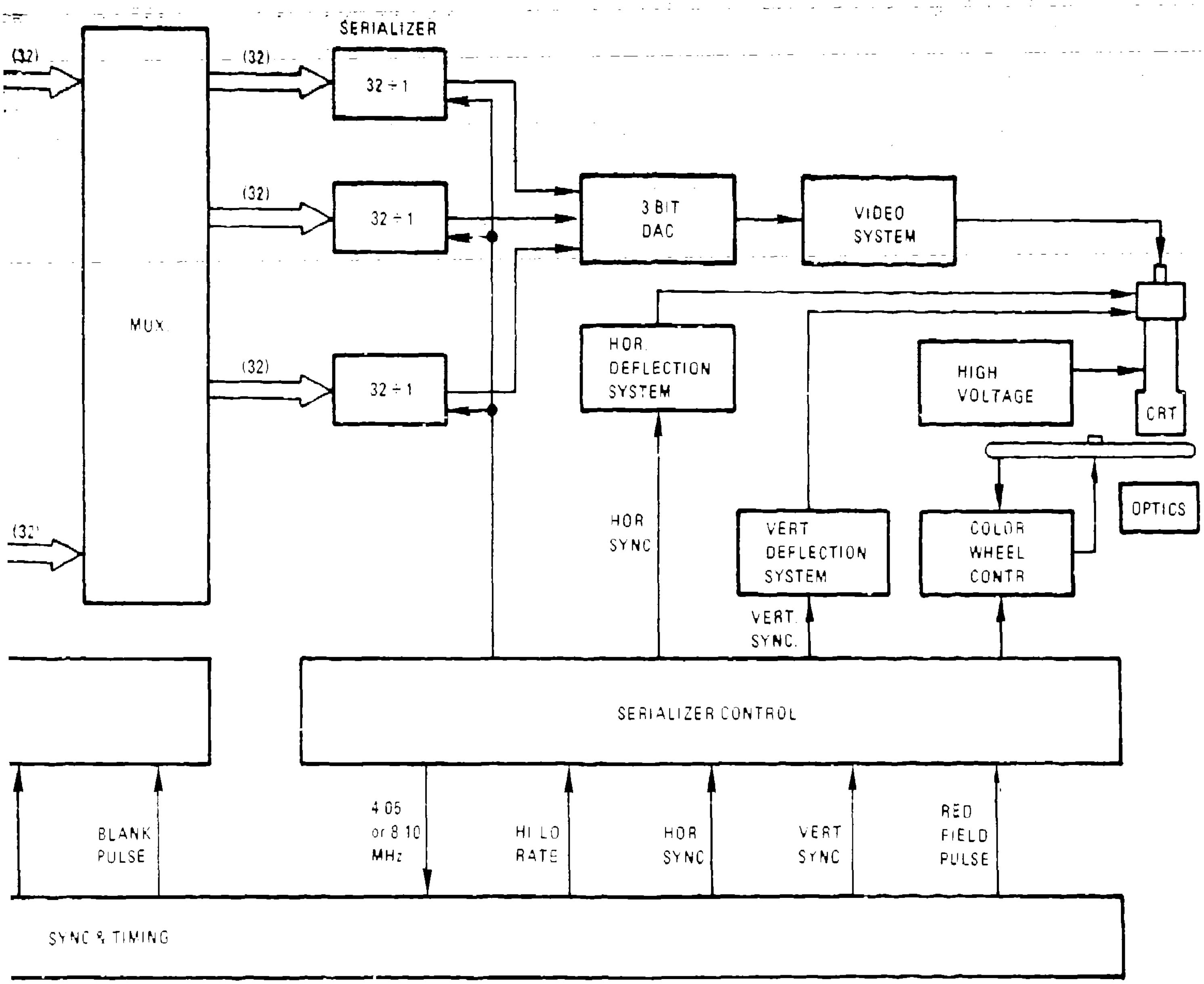


Figure 100 Mass Memory and Color Image Display

This system consists of five functional blocks which are described as follows:

a. High speed D/A converter
b. Serializer
c. Mass memory
d. Input controller
e. Sync and timing

Due to the fact that memory capacity and I/O data rates are all determined by the display, it is more meaningful to present the description sequence with the output device (high speed D/A converter), and describe in reverse order the other major sections of the display.

10.4.1 High Speed D/A Converter

The video system accepts low level information from a high speed 3 bit D/A converter. This converter is capable of converting digital data into analog data at a rate of 260 Mb/s. The 3 bits conversion provides 8 different intensities for each of the red, blue and green components.

The design approach of the converter is shown in Figure 101. A 3-bit binary word is reclocked into three MECL III flip-flops at a 260-MHz rate. The output of the reclocking flip-flops drive three individual bit sources which sum into a common 75-ohm resistor. The bit switch is comprised of two emitter-coupled pairs (Q_1Q_2 and Q_3Q_4) as shown in Figure 102. The function of transistors Q_1 and Q_2 is to square up the output of the MC 1670 flip-flop that has typical rise and fall time of 1.5 nanoseconds. The output of Q_1 and Q_2 has a rise and fall time of 1 nanosecond and a voltage swing of ±0.4 volts around ground. The transistors are type 2N5841 and have a gain bandwidth product of over 1 GHz. The output of Q_1Q_2 drives the emitter-coupled pair Q_3Q_4. The emitter currents of the bit switches are set in a binary fashion. The output is a constant current which, when switched into a 75-ohm resistor, has a rise and fall time of less than 0.8 nanoseconds and aberrations of less than one-half bit as shown in Figure 103.

Q_5 is a compensated zener diode and Q_6 ia a buffer that sets one side of the bit current resistors R_1, R_2, and R_3 to approximately -7.7 volts independently of supply variations. Q_7 is also a zener diode and Q_8 and Q_9 make up a buffer that feeds a positive current through

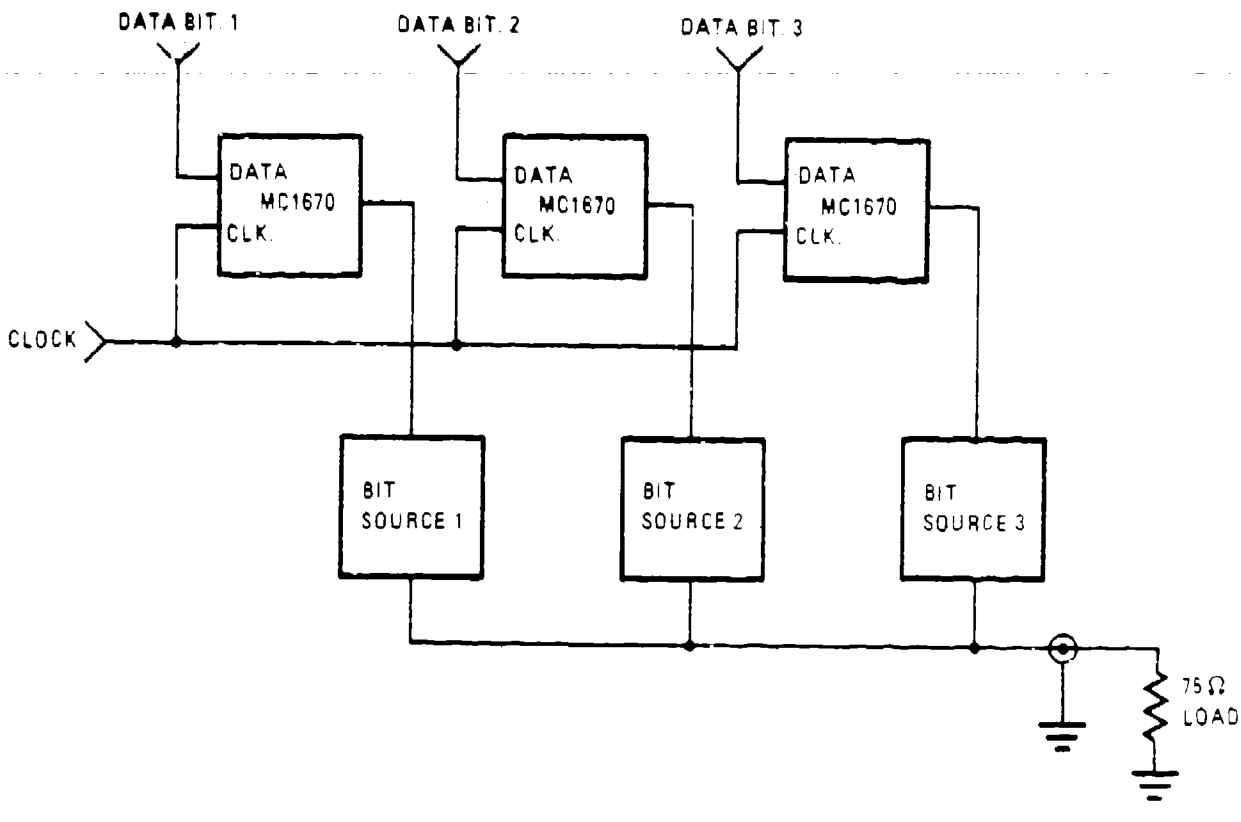


Figure 101 Design Approach Block Diagram

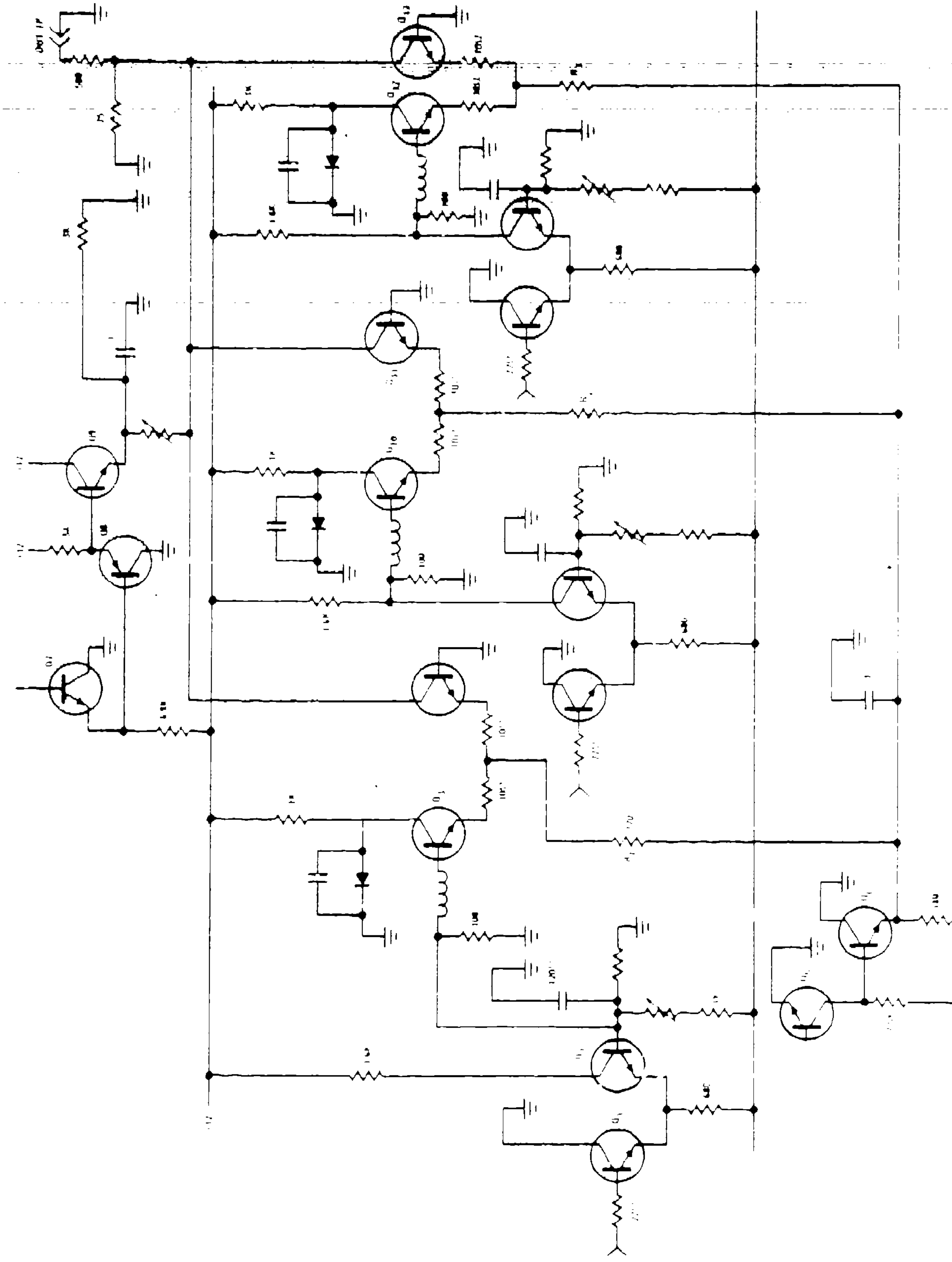


Figure 102 Bit Switches

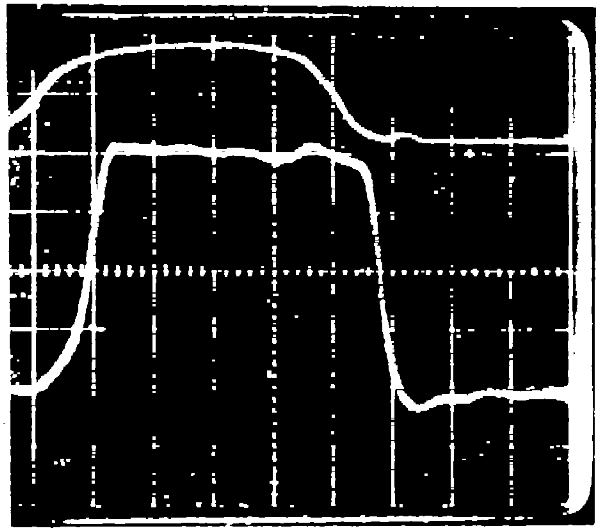


Figure 103 Output of Bit Switch into 75-Ohm Resistor

R_4 to the 75-ohm load resistor to provide a 1 volt output when all bit switches are off and a zero volt output when all bit switches are on. The bit switch transistors are HP high-frequency transistors, type 35823E, in a microwave package and a gain bandwidth of 7 GHz.

10.4.2 The Serializer

To provide 3 bit parallel data load to the D/A converter at a data rate of up to 260 mega words per second, a serializer has been developed to interface the mass memory with the D/A converter.

A block diagram of one channel of the selected 3-channel serializer design is shown in Figure 104. In this design the 32 input lines are split between four 8:1 mulitplexers. These four channels are then multiplexed in groups of two through two additional levels of multiplexing. This results in a final ratio of 32:1. The advantage of this type of serializer mechanization is that the 8:1 multiplexing level operates at 64-MHz clock rates that are compatible with low-cost ECL logic families. Since the bulk of the system circuitry is concentrated in this low-speed level, the remaining high-speed logic will occupy a small amount of board space.

A simplified schematic of the first level multiplexing stage (8:1) is shown in Figure 105. Four circuits, (as shown in Figure 104.) comprise the complete first level that multiplexes the 32 inputs to one channel onto four output lines.

The serializer receives its input data as differential signals on twisted-pair lines from the mass memory. These signals are received and translated to ECL logic levels by differential receivers. The output of the receiver is stored in a 4-bit storage register whose output is scanned by a 4:1 multiplexer. The outputs of two such multiplexers are then alternately selected by AND OR selection gates and loaded into the output flip-flop. The clock signal ΦC is used to load the output flip-flop and clock the counters which select the data lines to be used.

A timing analysis was performed using the worst case propagation delays for the circuit elements over the expected operating range of 0°C to 75°C. Propagation delays, due to capacitative loading of signal lines, were not included in this analysis. The timing diagram for the 8:1 multiplexer is shown in Figure 106.

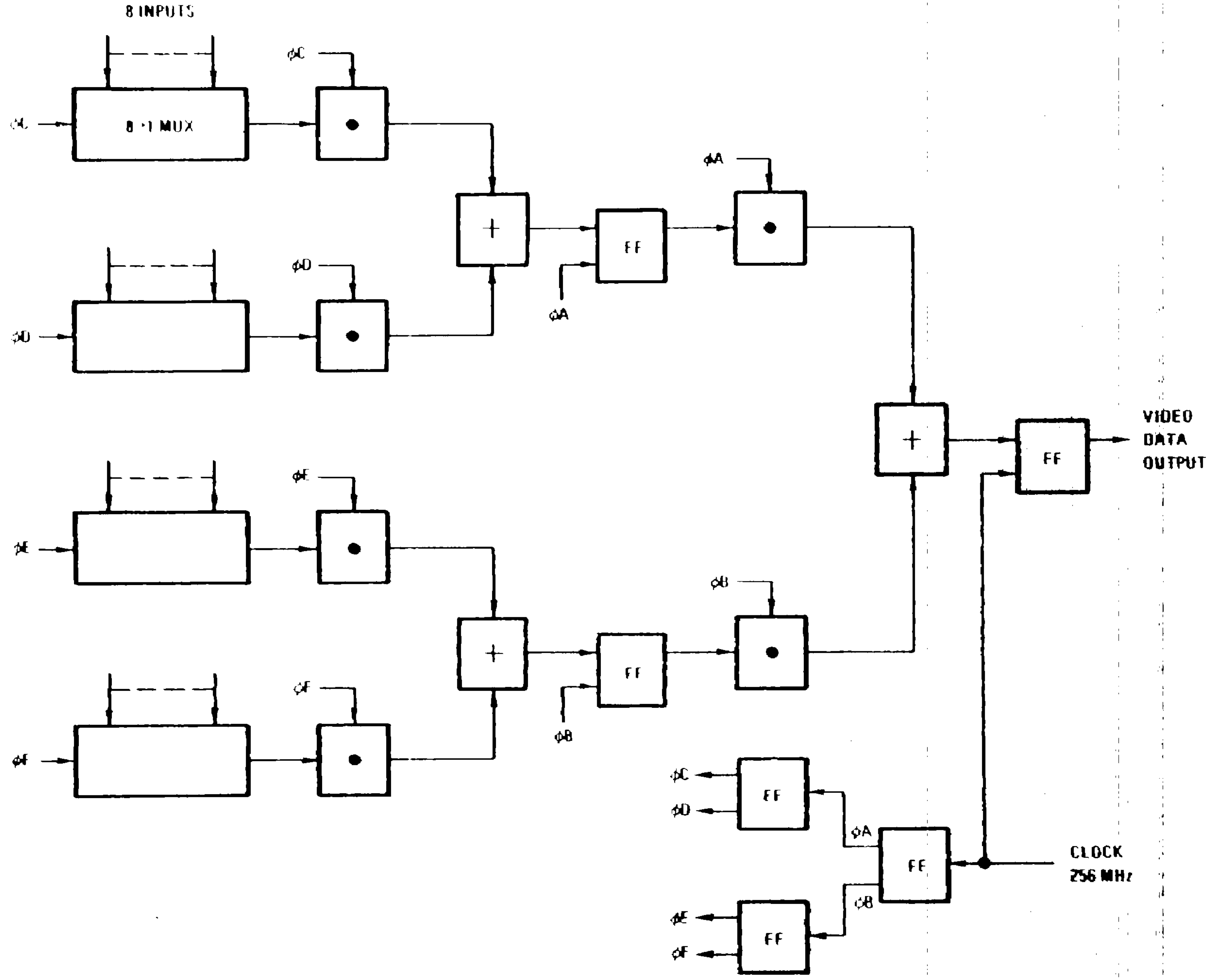


Figure 104 Serializer Block Diagram, Single Channel

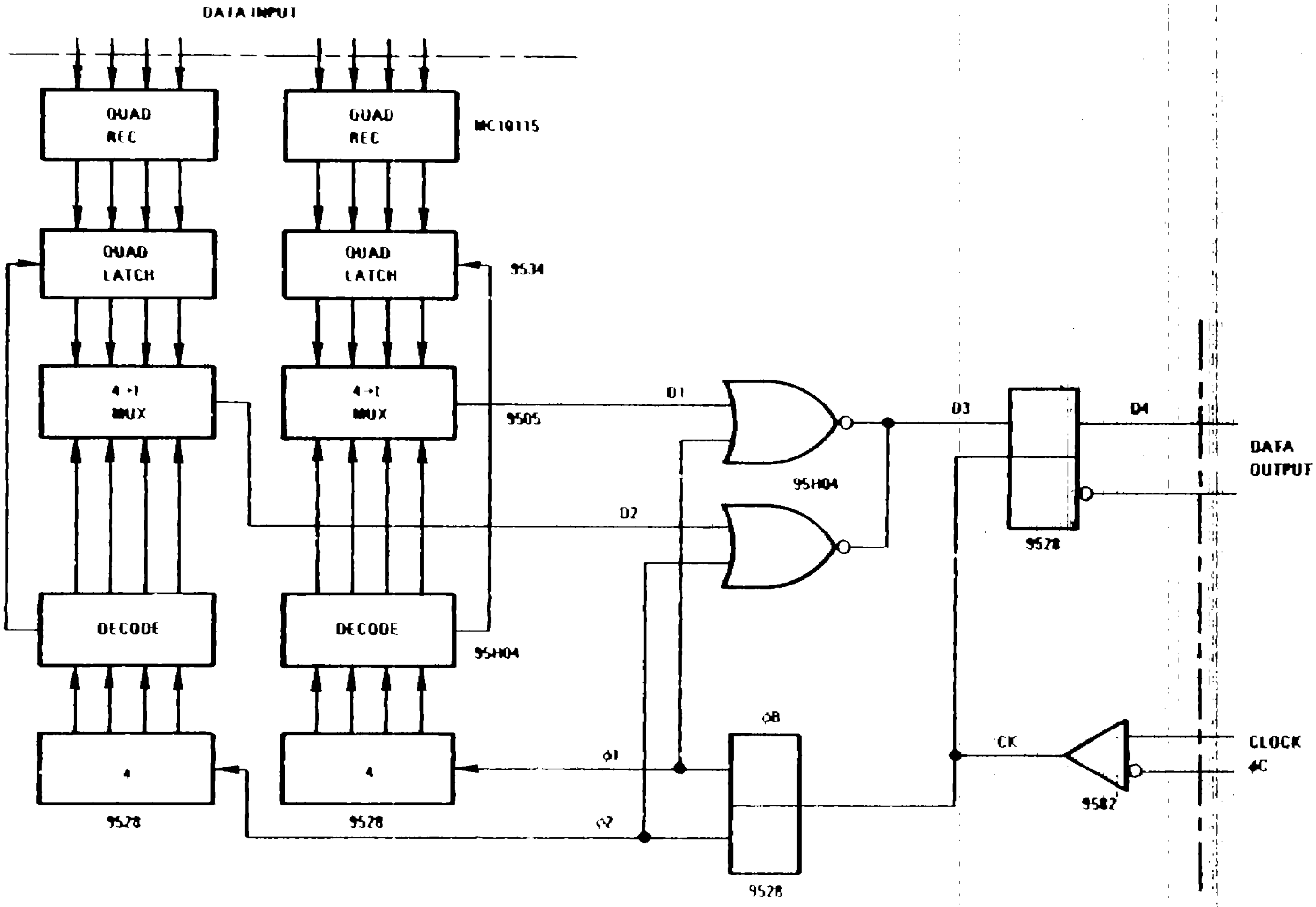


Figure 105 First Stage Seria er Schematic, Simplified

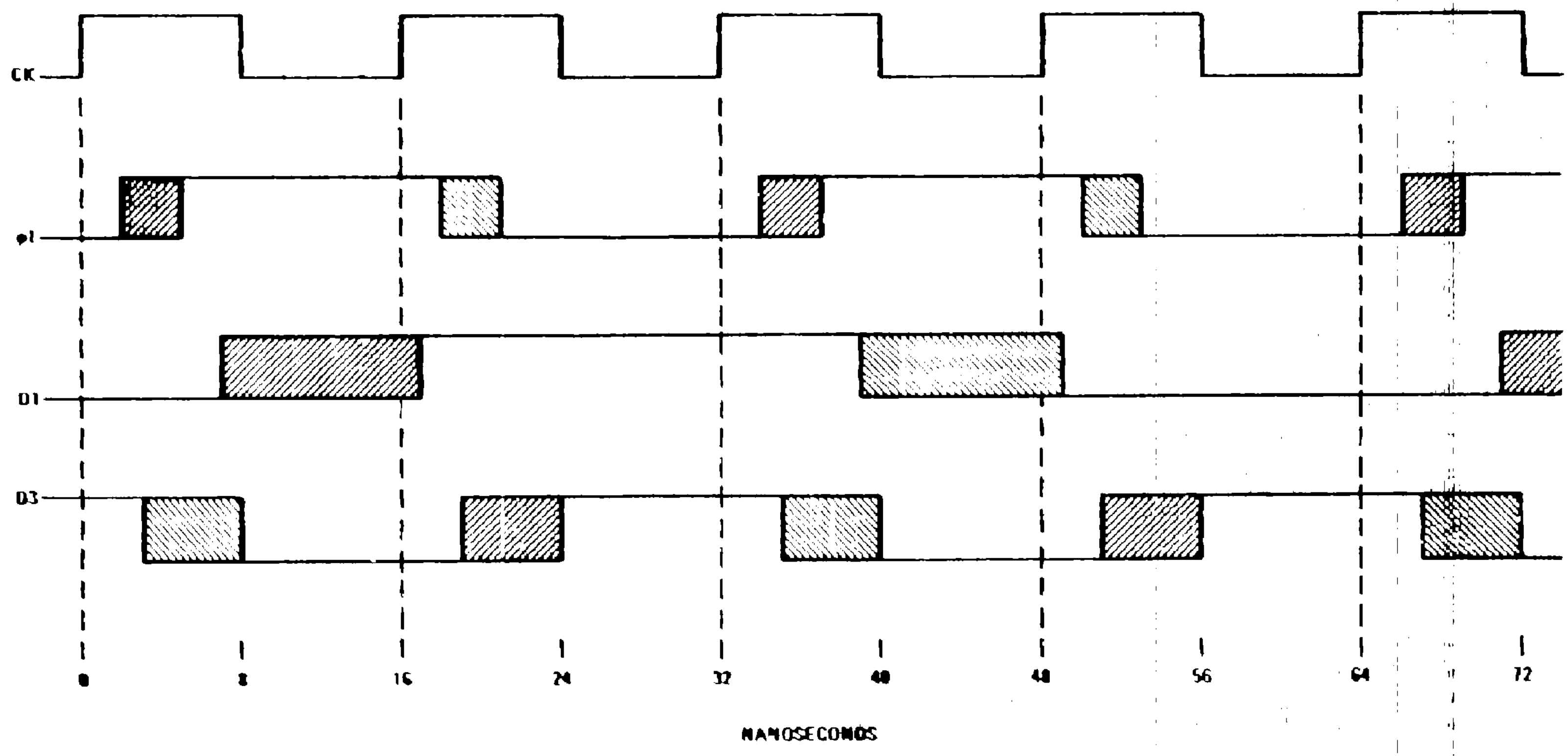


Figure 106 First Stage Serializer Timing

The second level of multiplexing is performed by the simplified circuit as shown in Figure 107. In this circuit the output of two of the 8:1 multiplexer stages are multiplexed, resulting in a 128-MHz output data rate. Two such circuits comprise the second level. A timing analysis was again performed as shown in Figure 108. The results of this analysis indicated that under the worst case allowed the data arrives at the output flip-flop 0, 1 ns prior to the rising edge of the clock. Since the flip-flop requires a maximum of 0.5 ns of setup time on the data input, it can be seen that the data would be 0.4 ns late. Typical circuit delays are also shown in Figure 10-9. Because of the large difference between the typical and maximum delays, it was decided to accept this design because of the minimal risk.

The third and last level of multiplexing is performed by the simplified circuit shown in Figure 109. In this level the outputs of two second level multiplexers, signals D_A and D_B, are multiplexed together to become the output of one of the three separate 32:1 serializers. The output data rate is 260 MHz. The timing analysis of the third stage serializer is shown in Figure 110.

The principal problems to this point have been the testing of many possible logical implementations using each ECL logic family produced by Fairchild and Motorola. One of the main difficulties encountered is that each ECL family has different signal levels and noise margins and are not compatible without level shifting which reduces the noise margins. The design presented here uses Motorola MECL 10115 receivers and the first stage is implemented with Fairchild ECL. Level shifting of the MECL is required to maintain noise margins at some decrease in circuit speed. However, this is acceptable since the data rate and timing at the receiver interface allow sufficient data settling time.

The second stage uses MEC III and MECL 10000 components which are directly compatible. The interface between the first stage and second stage logic is accomplished through a MECL III line receiver. This interface mates the Fairchild ECL with MECL logic at a cost of only one logic element propagation delay. The delays incurred through the high impedance level shifting networks introduce considerably more delay. The second and third stages are directly compatible since they are MECL III logic.

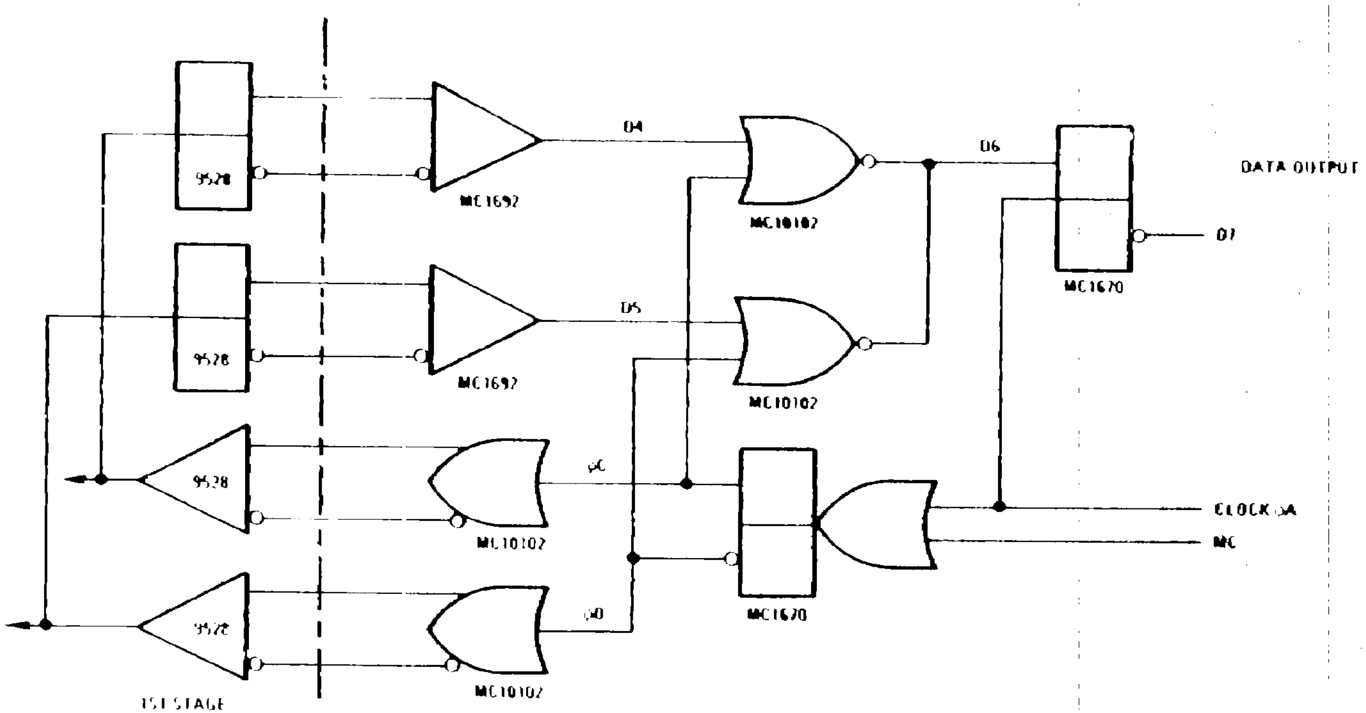


Figure 107 Second Stage Simplified Circuit

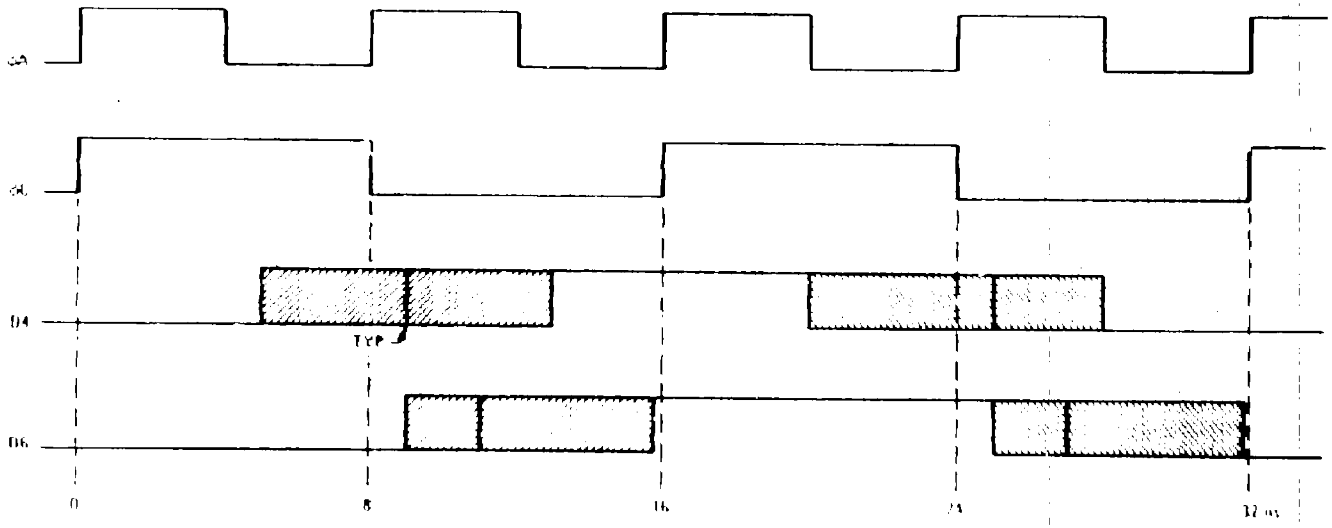


Figure 108 Second Stage Serializer Timing

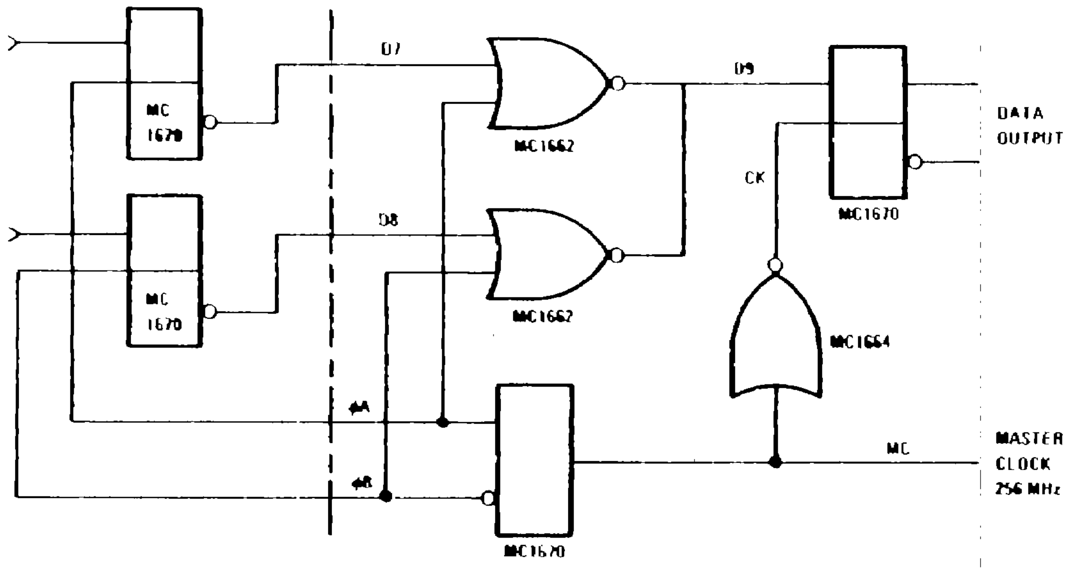


Figure 109 Third Stage Simplified Circuit

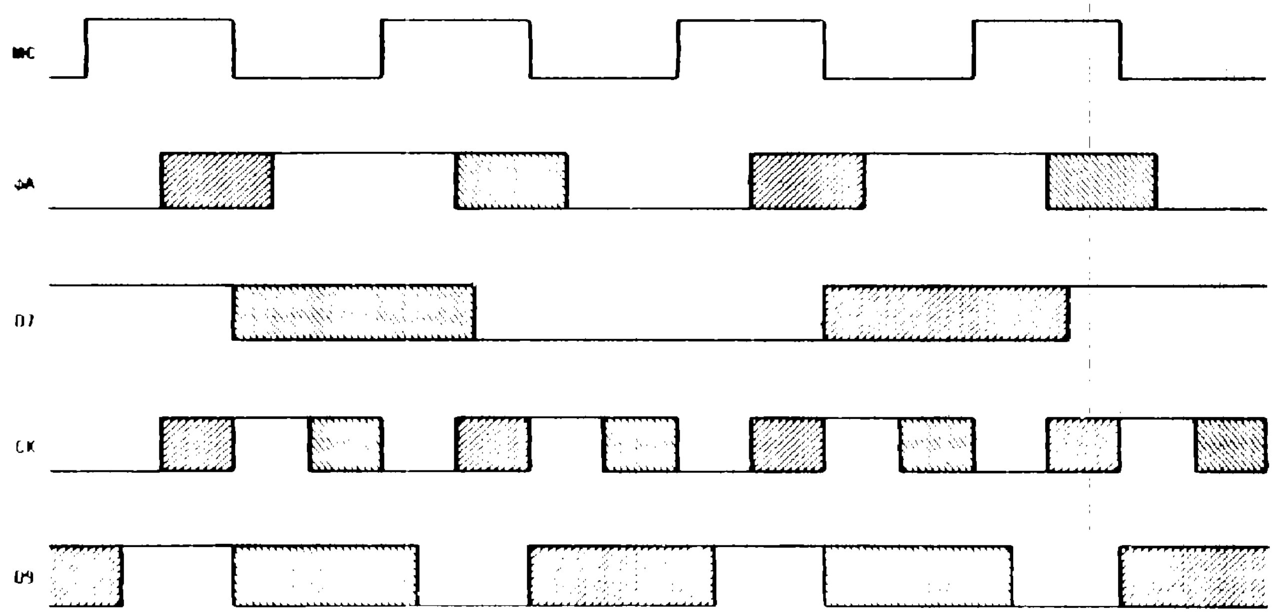


Figure 110 Third Stage Serializer Timing

MASS MEMORY

The function of the mass memory is to store an assembled color image frame and to repeatedly refresh the sequential color display at a rate commensurate with flocker free presentation.

A display having a resolution 1000 lines x 1024 bits with a 3-bit intensity control for each primary color, requires a memory with a storage capacity of 9×10^6 bits.

The memory is arranged as three 3-million bit memories, one for each primary color. Since the color fields are displayed sequentially, the outputs from these three memories are multiplied onto a common output bus.

Each of the color memories again consists of three one-million bit memories, one for each bit of intensity. This one-million bit memory becomes the basic refresh element. It is configured as an 8 K x 128 bit memory and assembled with eight 8 K x 16 bits MOS Refresh Memory Cards. This memory card permits up to three one-million bit refresh memories to be assembled in each basket, or one bit of intensity for the RG and B color components.

Since the refresh memory card is a major memory subsystem by itself, the operation of the mass memory is best understood by describing the basic memory card in detail.

10.4.3 MOS Refresh Memory Card

The basic refresh memory card is configured as an 8 K x 16 bit array of 128 1024-bit MOS shift registers. In addition, the card contains 16 MOS clock drivers, a quad input multiplexer, a 16-bit input buffer register, four output serializer stages, and six differential interface circuits for input and output data.

A block diagram of the MOS refresh memory card is seen in Figure 111, and a schematic diagram in Figure 112. A photograph of the prototype card is shown in Figure 113. This card is packaged to military specifications using a double sided 4 x E UPT printed circuit

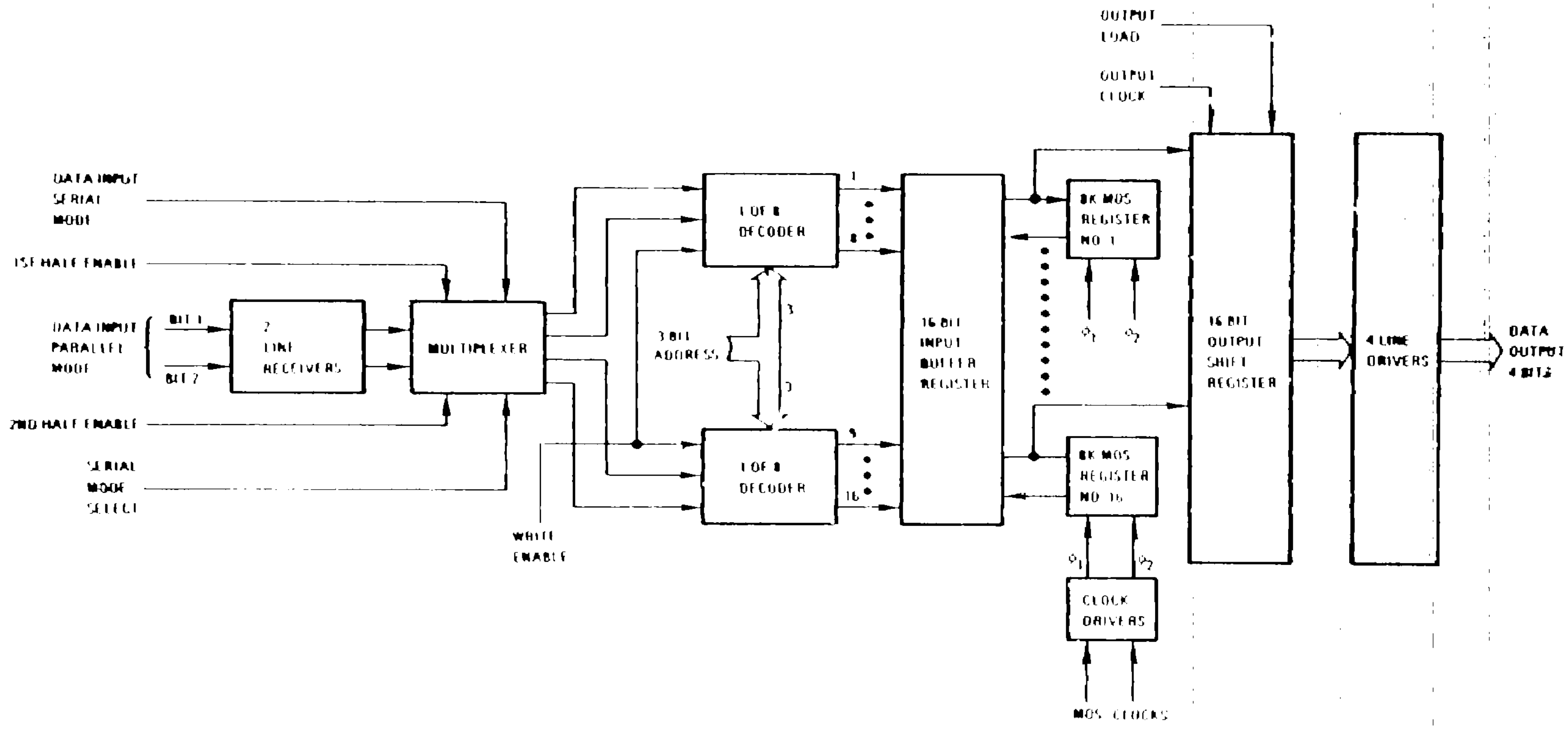
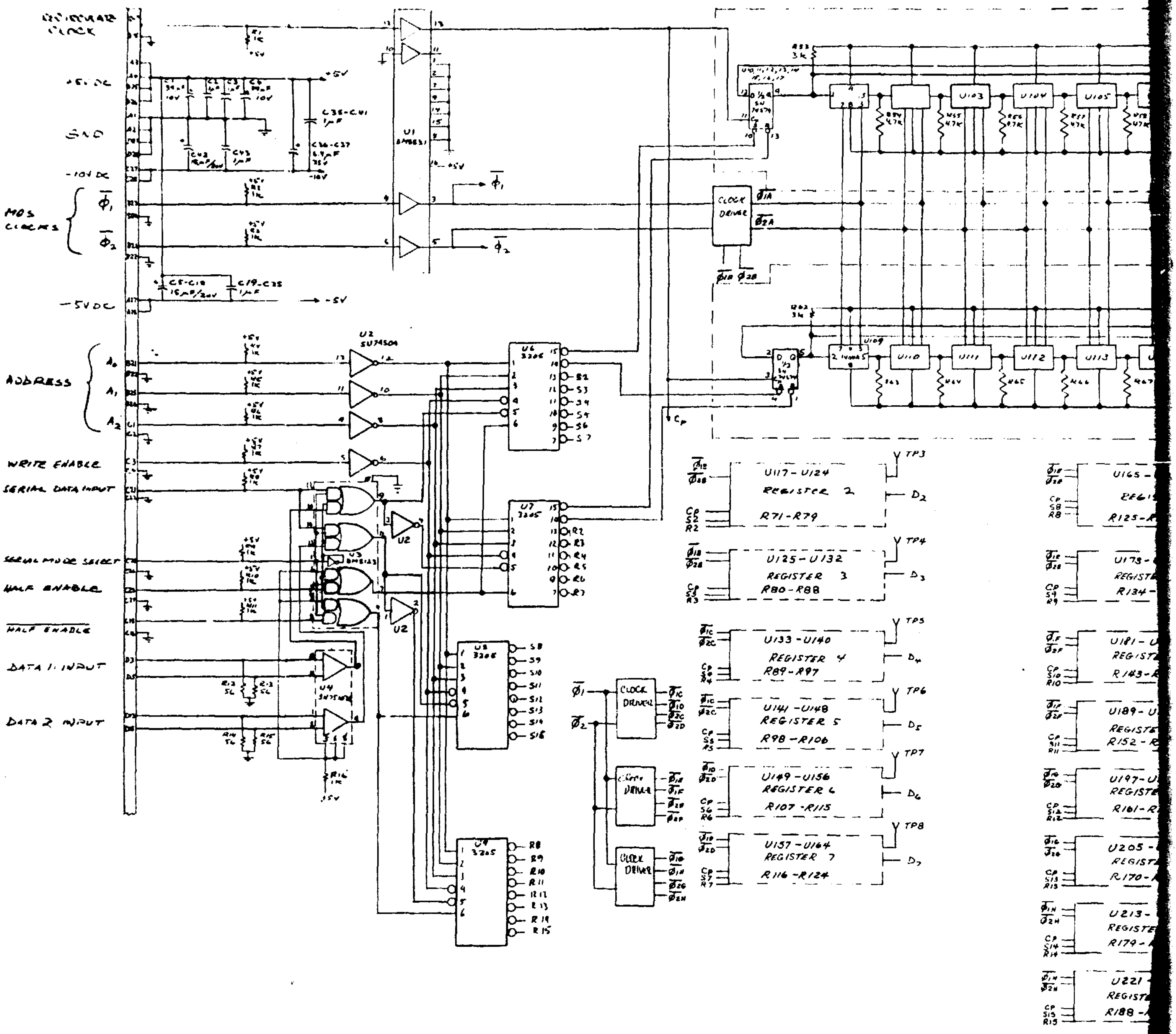


Figure 111 MOS Refresh Memory Card - Block Diagram

"PRECEDING PAGE BLANK-NOT FILMED."



1

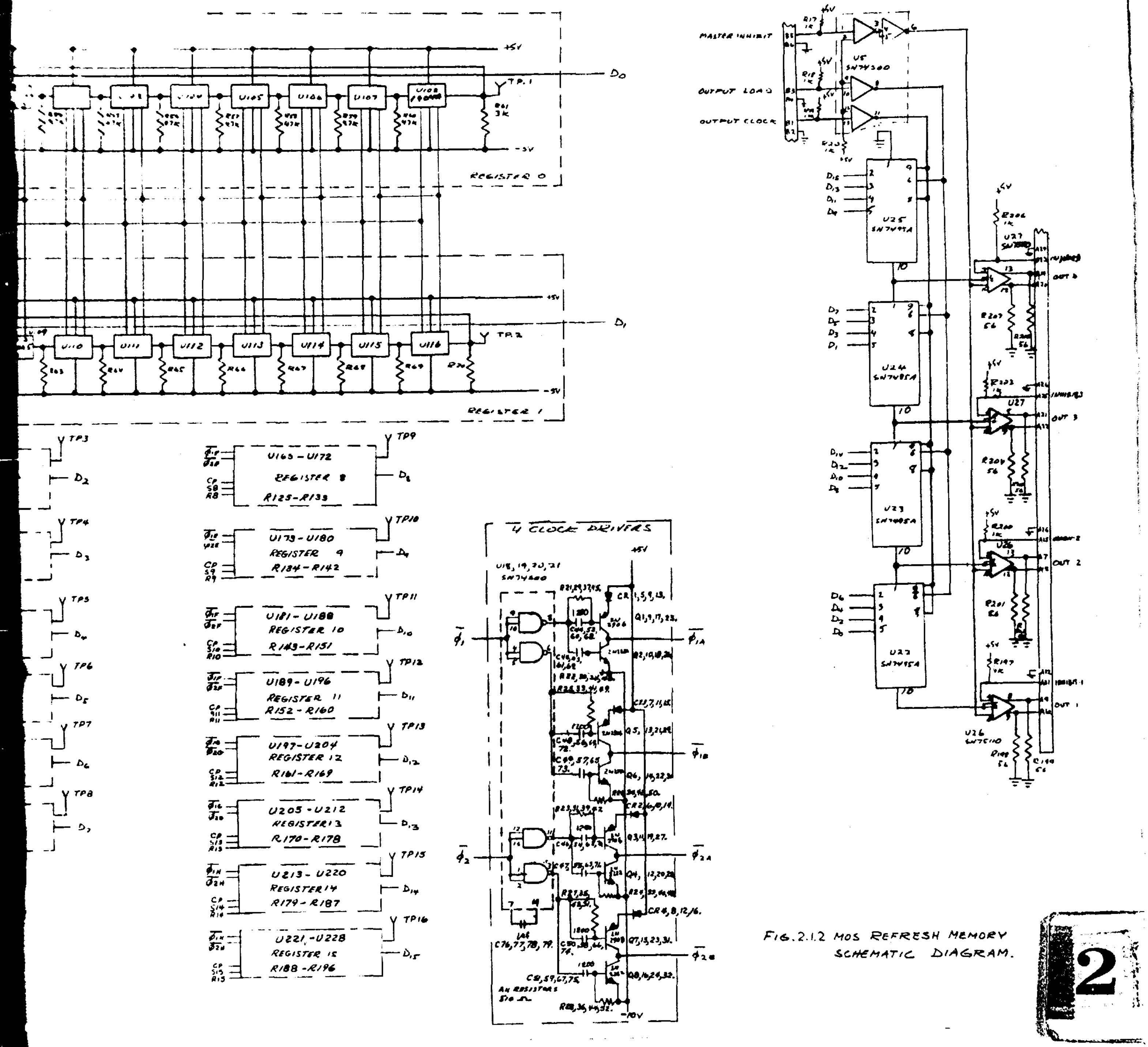


Figure 112 MOS Refresh Memory Schematic Diagram

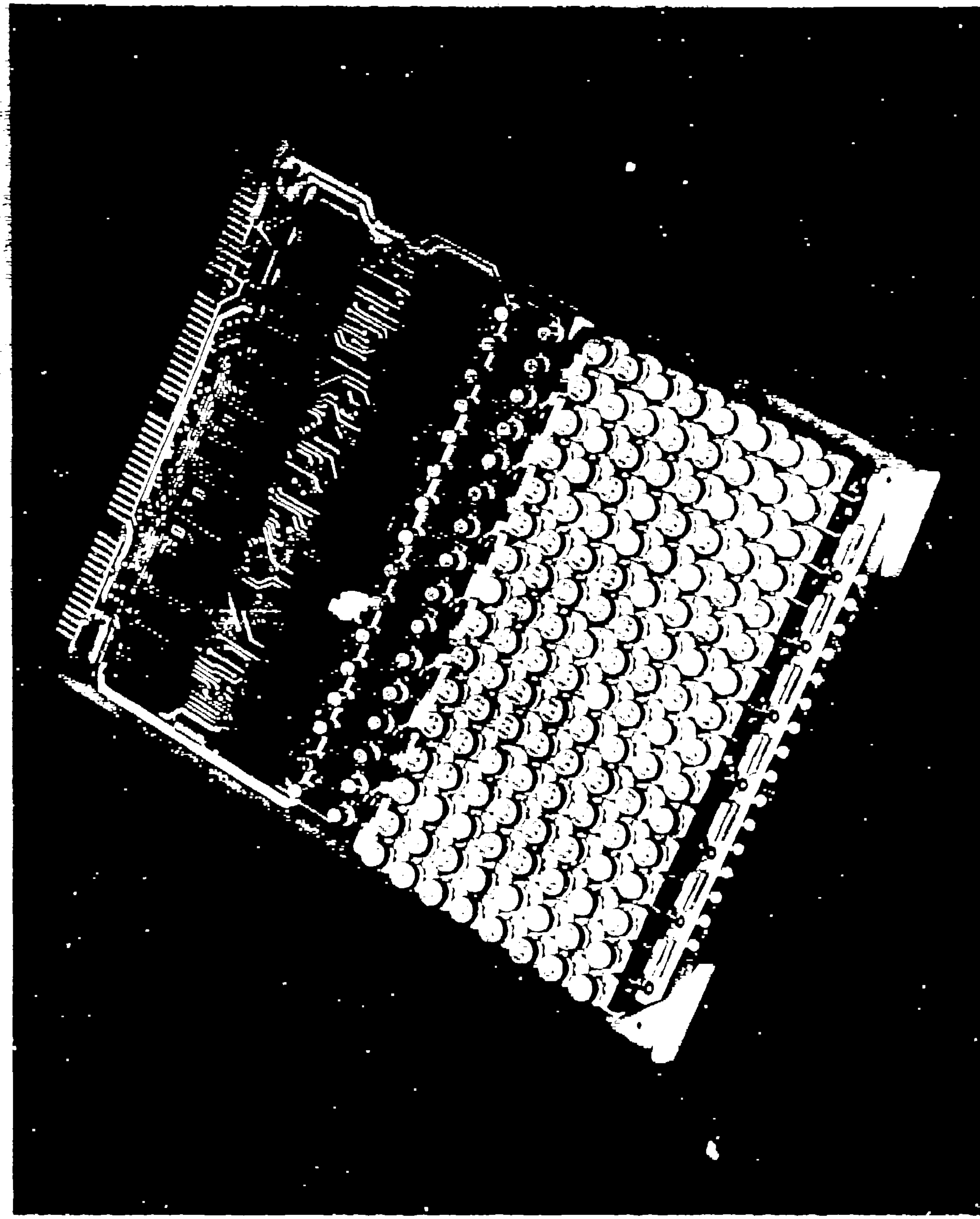


Figure 113 8K x 16 MOS Refresh Memory Card

wiring board. A clearance of 0.15" from edges to nearest traces allows it to be used with low profile metal retainer rails. Maximum height of assembled boards without sockets is 0.45". Card files with 27 slots on 0.6" centers may thus be used, permitting three one-million bit refresh memories to be assembled in a single 19" x 8.75" basket.

Circuit Description

The refresh memory circuits and their operation is described with reference to the schematic diagram in Figure 112 and the timing diagram in Figure 114.

MOS Shift Registers. Each of the 16 registers consists of 8 Intel 1404A MOS dynamic shift registers connected in series. The 1404A requires two clocks, ϕ_1 and ϕ_2. Data is shifted one bit on each clock pulse on either phase. Due to on-chip multiplexing the data rate is twice the clock rate.

The input to the shift register is driven directly from the input buffer register flip-flop SN74S74. This flip-flop enables the MOS register to recirculate data when a recirculate clock is applied, adding one bit of storage to the eight 1024-bit MOS registers.

Updating of the MOS register is accomplished through asynchronously setting or resetting the SN74S74 flip-flop. Output data to the serializer stages is taken directly from the buffer register outputs, thus enabling new data to be displayed as it is written into the MOS registers. This feature becomes an important diagnostic tool when the memory is used for refreshing CRT displays.

The MOS shift registers are capable of data rates up to 2 megabits, limited primarily by power dissipation on the card which at that speed totals 40 watts. A one-million bit refresh memory configured as 8 K x 128 and operating at 2 megabits bit rate, will provide a 256-megabit video signal when its outputs are serialized into a single video bit stream.

Input Buffer Register. This register consists of eight dual D-Type flip-flops, U10 through U17. Data is assembled in the 16-bit buffer register and then dumped into the MOS registers on the first MOS clock pulse. Data is written into the register through two data inputs and a three bit address during parallel mode, and through a single input line and a four bit address

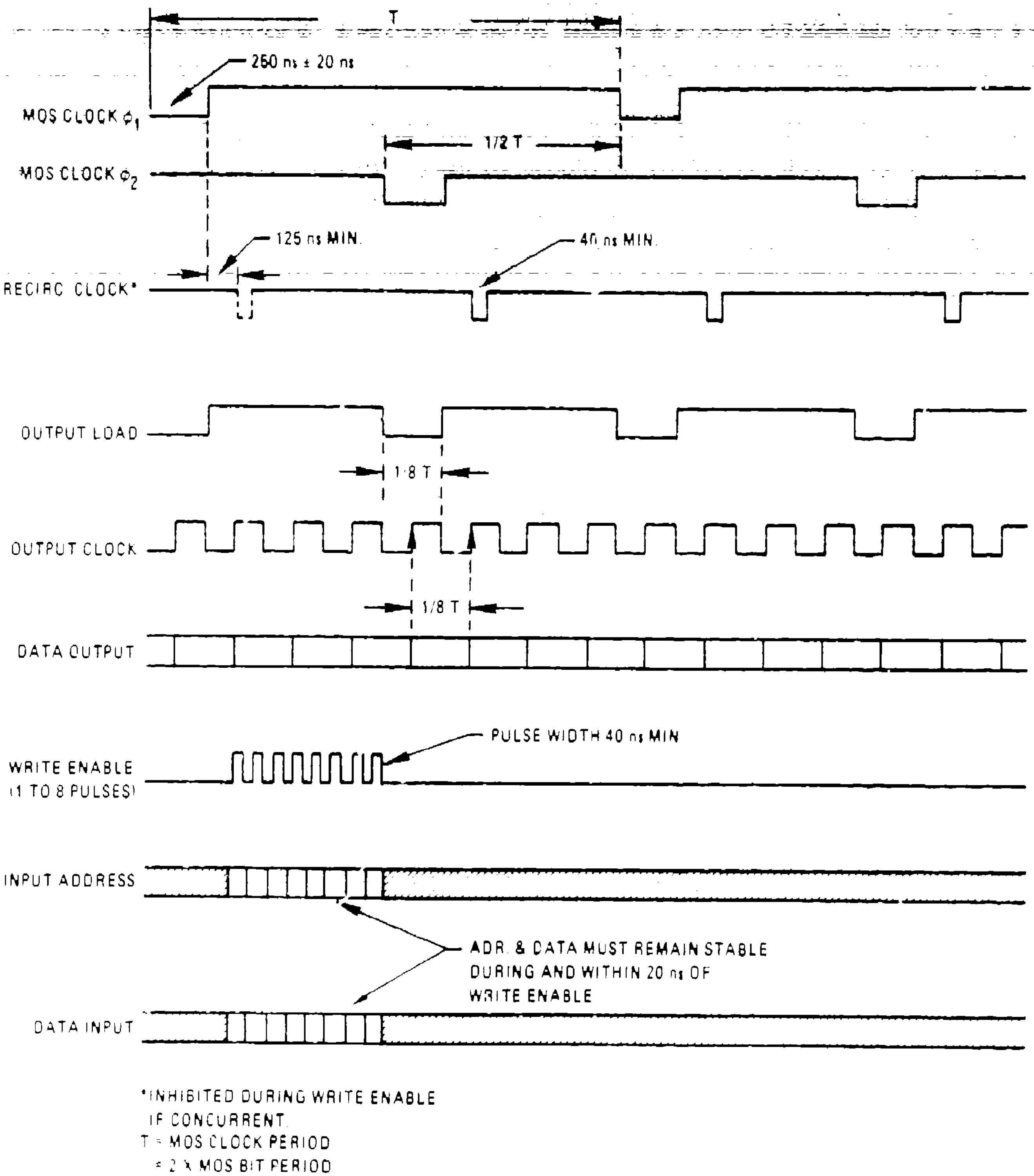


Figure 114 MOS Refresh Memory Timing Diagram

during serial mode. The addresses are decoded by U6 through U9 which will set or reset the proper flip-flops. These circuits are Intel 3205 1 of 8 decoders employing Schotky type logic. Each circuit is equipped with three enable inputs, pin 4, 5, and 6, which are operated by the data inputs, write enable inputs, and the half enable inputs. Half enable serves as the fourth address bit during serial mode.

The quad two-input multiplexer U3 selects between serial and parallel mode of operation through the "serial mode select" control line. In serial mode the buffer register is operated as a single 16-bit register, while in parallel mode it functions as two 8-bit registers, one for each data input line.

MOS Clock Drivers. Each clock driver provides 16 1404A MOS registers with one clock phase. A total of 16 clock drivers are required per card. The 1404A capacitive load is made up of the 140 pF clock capacitance and the 16 pF clock-to-clock capacitance. For 16 1404A shift registers total load on a clock driver amounts to 2500 pF maximum.

A circuit diagram for the clock drivers is also found in Figure 111. The clock driver consists of an SN74S00 gate driving a 2N2906 and a 2N2222 transistor in push-pull. The clock lines are thus clamped to -10 volt during a clock pulse, and to a level one diode drop below -Vcc during the interval between pulses. This satisfies the high voltage level requirement of Vcc +0.3 -1 volt for the 1404A clock inputs. It is important that the clock lines are clamped firmly to the high level to prevent cross-coupling between the clocks through the 256 pF clock-to-clock capacitance.

Output Serializer. The function of the serializer located on the refresh memory card is to reduce the number of outputs per card from 16 to 4 in order to simplify wiring within the refresh memory rack and to reduce the number of cables required for data transmission to remote displays. However, this increases the maximum data rate per output by a factor of 4 to 8 megabits NRZ, or 4 MHz. Such a bit rate is still low enough to allow data transmission over 1000 feet of balanced cables.

The serializer consists of four 4-bit shift registers U22 through U25. These are the SN7495A high speed registers capable of shift rates in excess of 35 megabits. The serializer may be operated as four 4-bit registers, two 8-bit registers, or one 16-bit register.

Serializer timing is shown in Figure 114. Data may be loaded during the time interval between recirculate clock pulses. In the diagram the "output load" pulse is generated from the two MOS clocks. Shifting of the output data occurs on the positive going edge of the output clock. All four outputs are shifted simultaneously.

The outputs are transmitted by the SN75110 balanced line drivers U26 and U27. Inhibit lines are provided for each output as well as a master inhibit. Outputs are enabled when inhibit lines are high. The inhibit functions enable multiplexed operation where serveral memories are sparing a common output bus.

Operational Modes

The refresh memory card has two modes of operation, serial and parallel. A one-million bit memory operating in serial mode may be updated through a single data line, while in parallel mode it will be updated through a standard 16 bit data interface.

Selection between the two modes is provided by the input control "serial mode select." A logical "0" operates the card in serial mode, while a logical "1" switches it to a parallel mode.

10.4.4 Input Controller

The input controller provides the interface between the input device or sensor and the mass memory. Each input device requires a unique controller. Depending upon the input device or sensor, the controller may contain another memory in order to improve the excess time of the overall system.

When displaying a 1000 line interlaced field, the maximum random excess time of the mass memory is 4 msec, and the average random excess time will be 2 msec.

When high speed input devices are used with storage and sync capabilities, excess times of 0.5 microseconds can be achieved. Due to the wide range of input devices and sensors presently on the market, a separate paragraph is used to describe the potential capabilities and the problem areas of the mass memory interface with other input devices.

The following description of the PDP-11 interface with the mass memory reflects the interface presently being incorporated.

10.4.5 PDP-11 Input Controller

The PDP-11 input controller provides storage for a 16-bit output word of the PDP-11 computer. Data is being transferred one word at a time from the computer to the mass memory.

Figure 115 shows the block diagram of the input controller interface. The device contains 2 storage registers. One 16-bit storage register for data transfer and one 18-bit storage register for address storage and transfer are use.

Data may be transferred with 16 bits at a time. 13 bits of address are used to address the 8K memory. Three bits of address are used to select the 16-bit word location in the 128 bits wide memory and 4 bits to select one of the nine 1-million bit memories.

Data and address transfer between the PDP II and the input controller are controlled by the MSYW and SSYW control signals. This interface is based on the basic request acknowledge principles. After data is transferred from PDP II to the storage register, the controller control logic will raise the Input Data Request line and place the data and address on the data and address lines respectively.

The 13 bits address is compared against the 13 bits address counter in the Sync and Timing logic. When a comparison has been reached, data will be strobed into the mass memory input register and an Input Data Acknowledge (IDA) will be sent to the input controller. When this IDA is received by the controller logic the output data request line (SSYN) will be raised again to request a new output data word.

As shown in Figure 115, the data and control lines outputs are all connected to a buss. This approach will simplify expansion of the number of input controllers.

The PDP-11 input controller is built on two 4 x E/UPT wire wrap cards. These two cards are located in a basket which also contain the sync and timing logic.

10.4.6 Sync and Timing Logic

The sync and timing logic controls the sync of the data flow from the input controller to the CRT display. Figure 100 shows the control signals between the input controller, refresh memory, serializer and the sync and timing logic. All control signals are derived from the 4.05/8.1 MHz load clock received from the serializer. Figure 116 shows a block diagram of the sync and timing logic.

Each 3-million bit memory has its own address logic. During the time that one 3-million bit memory refreshes the display, the other two 1-million bit refresh memories are operating at half speed. The purpose of this approach is to minimize the power dissipation in the memory basket. By halving the dissipation on two of the three 1-million bit memories the power will be reduced by 1/3 per basket.

Storage of new data from the computer into the memory is accomplished in the following manner. Whenever data is ready for storage in memory, the address is placed on the address lines and an Input Data Request (IDR) is generated. The sync and timing logic will compare the 13-bit address from the input controller against the address of the corresponding memory counters. When the comparator detects identity, the memory is ready to accept data in the memory location as specified in the address.

When a valid comparison is made, an Input Data Acknowledge (IDA) is generated and sent to the input controller. After detecting the IDA, the input controller strobes the data into the input register of the mass memory.

The sync and timing logic also generates the horizontal and vertical sync pulse and the red field pulse.

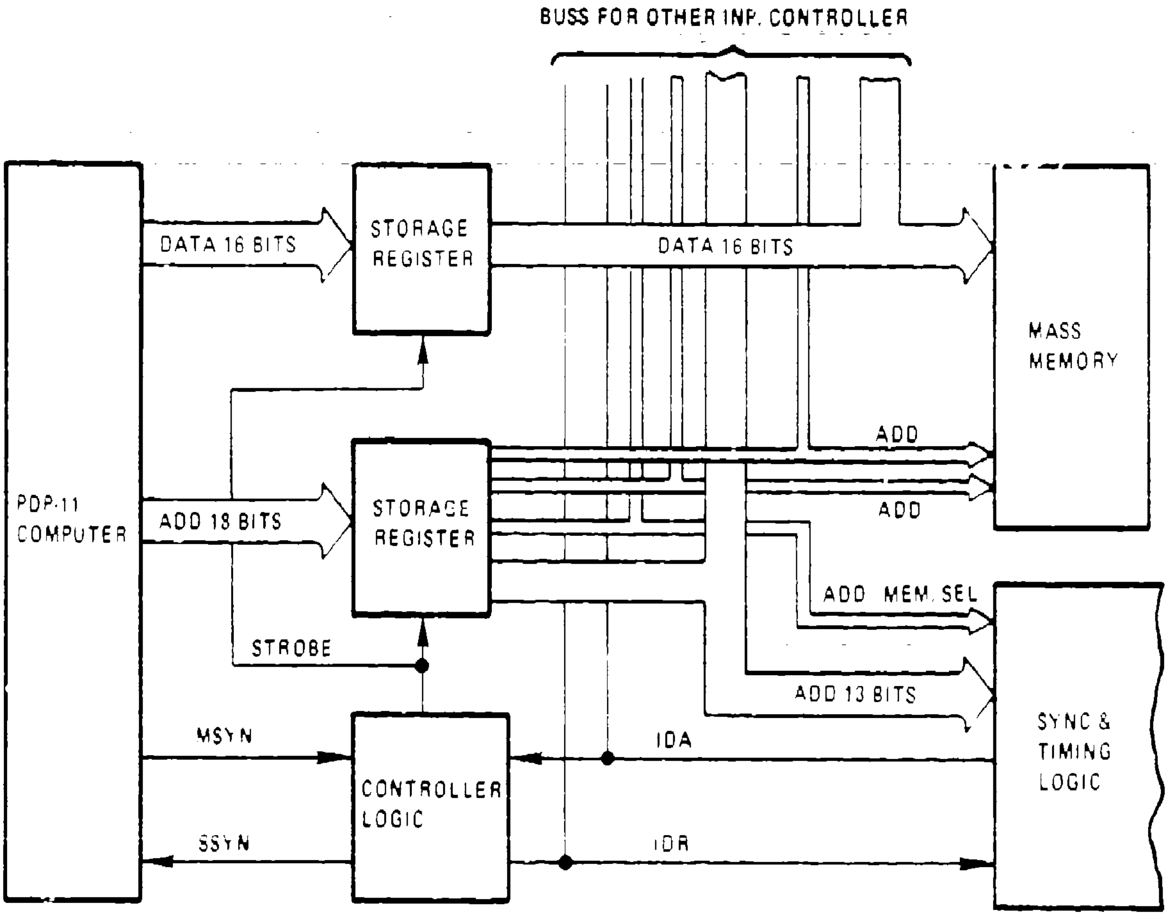


Figure 115 PDP-11 Input Controller Block Diagram

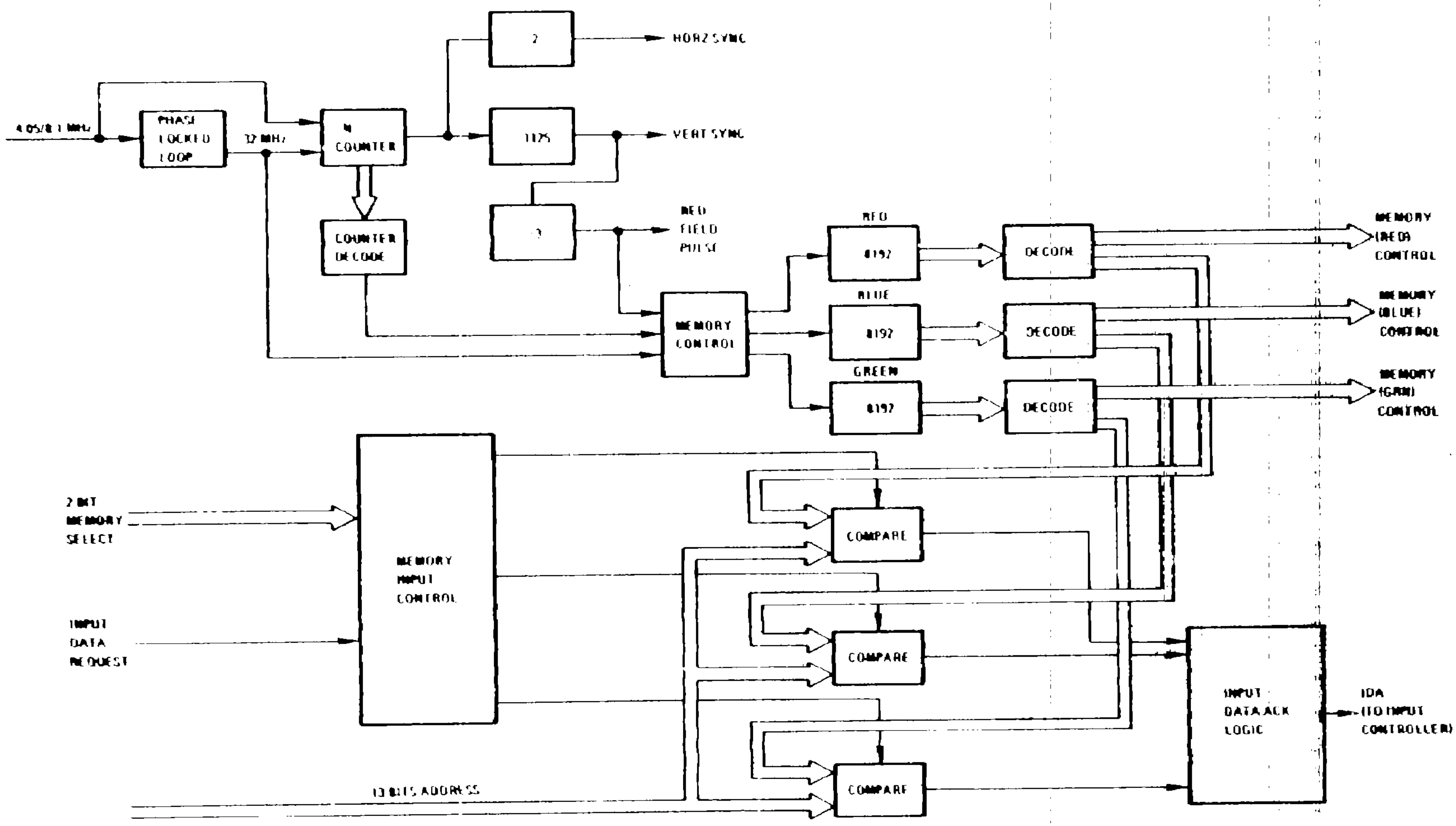


Figure 116 Sync and Timing Interface Block Diagram

Figure 117 shows the timing diagram for the sync pulses of a 1125/2 line interlaced colored field. For each three vertical sync pulses, one red field pulse is generated. To arrive at the correct sync wave forms, the total number of lines for non-interlaced scans are defined in one primary frame as the odd number 1125. However, the number of visible lines are 1000 while 125 lines are blank and occur during vertical retrace.

The total number of lines for interlaced scans are 1125/2 lines and the number of visible lines are 500.

Therefore, the horizontal line rate for the non-interlaced scan is:

$$3 \times 1125 \times 60 = 202,500 \text{ scans/sec}$$

The horizontal line rate for the interlaced scan is:

$$3 \times 1125 \times 30 = 101,250 \text{ scans/sec}$$

10.5 SENSOR INTERFACE

The various types of sensors or information storage devices intended as data sources for the color display are described in Section 10.2. A summary of these sensing devices and their video frequency responses are listed in the following table.

Device Type	Bandwidth
Laser Scanner	< 1 MHz
Magnetic Tape	< 5 MHz
Video Discs	< 2 MHz
LLLTV & TV Cameras	<32 MHz

The camera bandwidths exceed the 5 MHz data rate capability of the design originally contemplated. The interface design described will be based on the 5 MHz capability.

A block diagram of the sensor-to-refresh memory interface design is shown in Figure 118. Only one of each type of sensing device is shown. However, the number of input channels could easily be expanded merely by adding multiplexer channels.

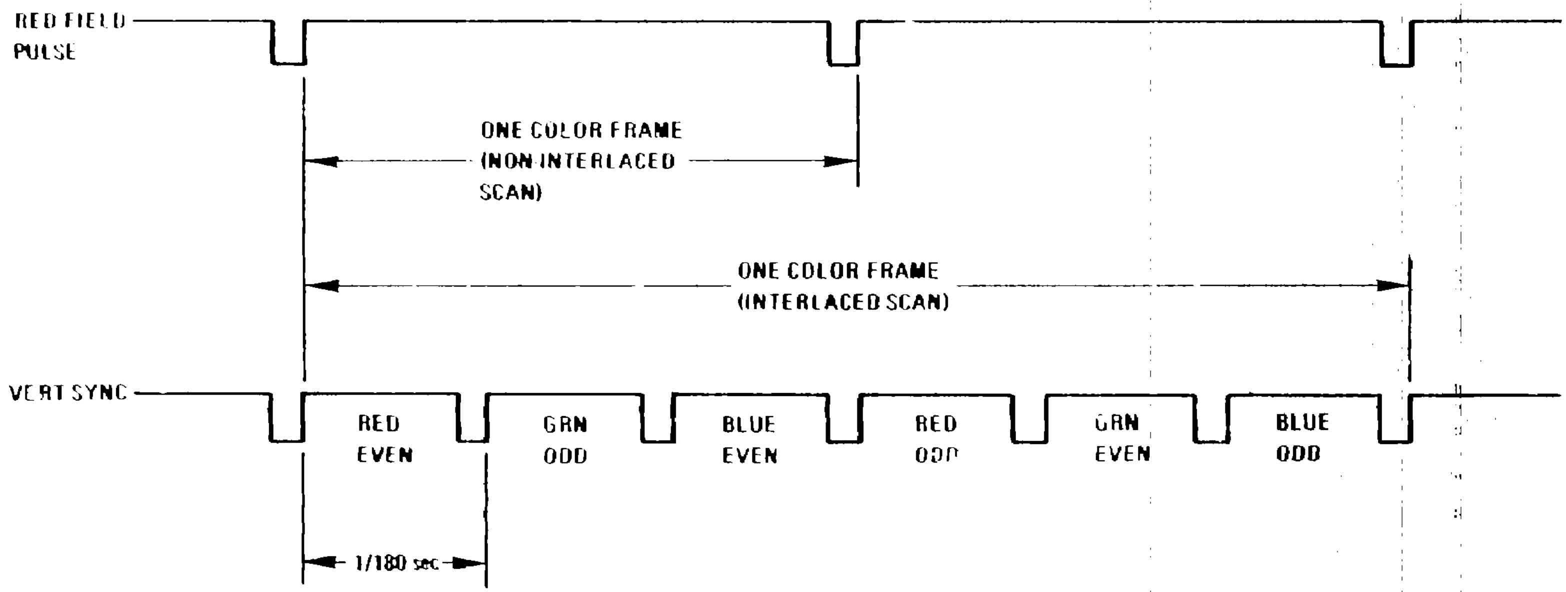


Figure 117 Display Sync Timing Diagram

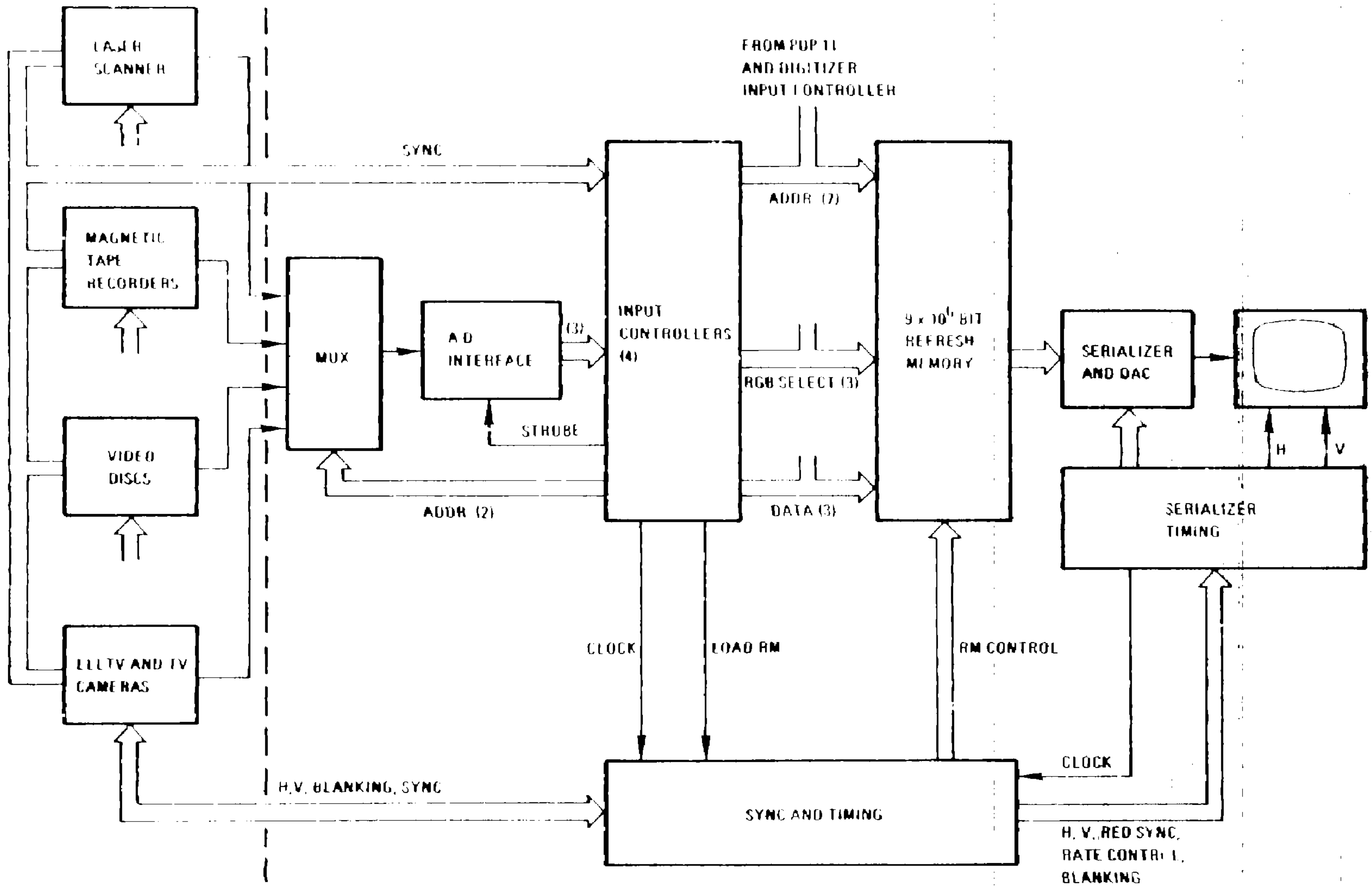


Figure 118 Sensor-Refresh Memory Interface

Parallel input capability of all channels is achieved through sequential addressing ie multiplexer, incrementing the multiplexer address for each frame processed. By stopping the multiplexer at the desired channel and holding it indefinitely, sequential inputs from the same sensor may be accommodated.

Inputs to the display may be either interlaced or non-interlaced. The display will reformat both types into sequential color interlaced video frames for display presentation by storing one field in each half of the RGB refresh memories.

H and V drives, blanking, and sync signals could be made available from Sync and Timing for use with any of the four types of sensors. Where self-contained sensors are used, the respective input controllers will receive separate sync lines from the sensors. Phase-locked loops will be required in each input controller to ensure 1024 A/D conversions per horizontal line. The input controller in turn selects and inputs 3-bit words to the RGB refresh memories.

In order to maintain a 1-for-1 relationship between horizontal scans on display and sensors, the refresh memory during the write mode is slowed down to match the speed of the sensor. It also follows that there will be a 1-for-1 relationship between vertical scans. Since the display utilizes 1000 visible lines of resolution in two interlaced fields for each primary color, sensors with resolutions of less than 1000 lines interlaced and less than 500 lines non-interlaced will only partially fill the display. On the other hand, sensors with higher resolution will lose the lines exceeding the capability of the display.

10.5.1 Data Sampling

In order to determine the conversion speed requirement for the A/D converter, the errors associated with sampled data systems must be analyzed.

The sampling theorem states that in order to reproduce a band-limited signal f_d, the sampling frequency f_s has to satisfy the relationship $f_s \geq 2 f_d$. The video signals received from the sensors are not band limited, but may be assumed to have a high frequency roll-off of 6 dB/octave. Thus the video signals will be contaminated with high-frequency noise components giving rise to aliasing errors if sampled at too low a rate.

The frequency at which $f = f_s/2$ is called the Nyquist pole. Any data beyond the Nyquist pole is irretrievably lost and normally should be prevented from causing additional errors through aliasing. This could be accomplished by installing a pre-sampling filter with its corner frequency set at the Nyquist pole and with a very sharp cut-off.

Graphs of aliasing errors for various sampling rates are shown in Figure 119. The errors are based on a data cutoff rate of 6 dB/octave and on the assumption that all signal components past f_d represent noise.

For an aliasing error to be commensurate with the 1/2 LSB quantizing error of a 3-bit A/D converter, it should not exceed 6.25%. Extrapolating sampling ratio from Figure 119 for this error yields a value of approximately 20. A 5 MHz video signal will therefore have to be converted at a rate of 100×10^6 conversions/second to achieve a combined aliasing and quantizing error of less than 12.5%.

Another source of error which is extremely important when sampling high-frequency signals is the error associated with the aperture time of the A/D converter, or a sample and hold circuit preceding the converter. Since most high-speed A/D converters employ parallel conversion, i.e., all bits are determined simultaneously, sample and hold circuits are not required. The aperture time in an A/D converter is the time it takes to perform a complete conversion, which in a parallel converter becomes the skew time between the fastest and slowest bits.

Aperture errors are plotted as a function of aperture time and signal frequencies in Figure 120. In order to limit this error to 6.25% at 5 MHz, the maximum aperture time allowed is found to be 2 nanoseconds.

10.5.2 A/D Converter

The fastest A/D converters available today have conversion rates in the range of $10\text{-}15 \times 10^6$ conversions/second. Such instruments have resolutions of 6 to 8 bits and accordingly are slower than they need to be for 3-bit applications. American Astrionics, Inc. has 6, 7 and 8-bit converters at 10 Mw/s which start at $5,375, while Datel Systems, Inc. has an 8-bit

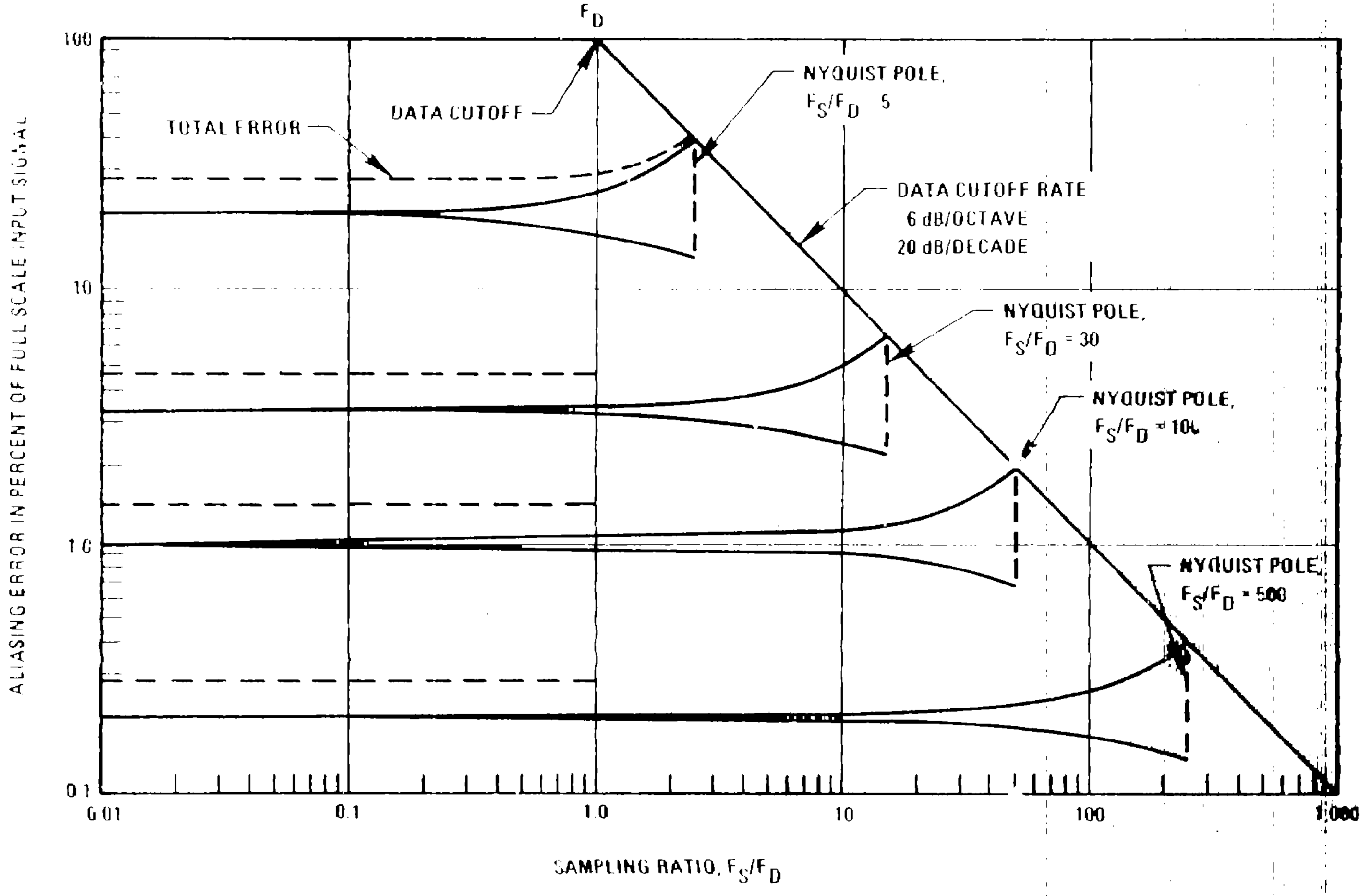


Figure 119 Aliasing Error Curves for Various Sampling Ratios; Data Cutoff Rate, 6 dB/Octave

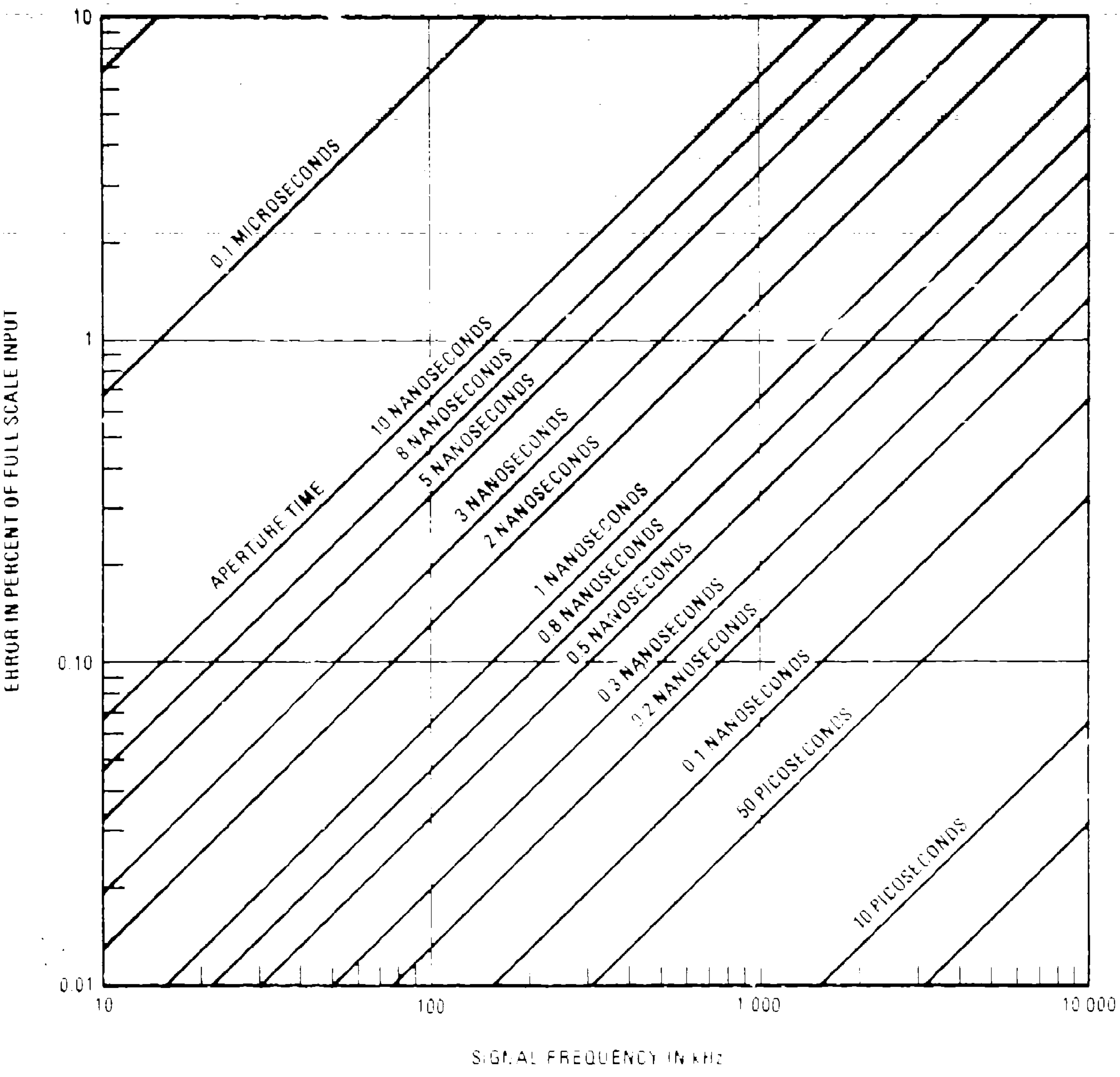


Figure 120 Error Due to "Aperture Time" as a Function of Frequency

converter at 15 Mw/s costing $1,195. These converters are too slow for converting 5 MHz signals with some degree of accuracy.

An A/D converter, or digitizer, which is ideal for sequential color application is depicted in Figure 121. This 3-bit digitizer will track video signals up to 20 MHz with a maximum error of one LSB. At 20 MHz the minimum time required for a sine wave signal to change by an amount equal to the LSB is 1 nanosecond. This means that the LSB will toggle at a maximum rate of 500 MHz which is compatible with the MECL III logic used.

Extrapolating further, the digitizer will have an accuracy of 2 LSBs at 40 MHz video and 4 LSBs, or 50%, at 80 MHz.

This digitizer has two modes of operation. It can track and digitize an analog signal continuously, or it may be switched to a hold mode which holds the digitized signal indefinitely. Aperture time in hold mode is typically 1 nanosecond.

The key to this digitizer is the MECL III comparator latch device which offers high input impedance and allow offset voltage of 5 mV. For a 1V video signal this offset represents an error of only 0.5%. The reference voltage V_R is set equal to the full scale of the input signal.

Data may be written into each refresh memory at a maximum rate of 20 Mw/s, or 50 nanoseconds per 16-bit word. It takes 16 A/D conversions to assemble one word. The required conversion rate to fully utilize the speed capability of the refresh memory is therefore $16 \times 20 \times 10^6 = 320 \times 10^6$ conversions/second, which is within the capability of the described 3-bit digitizer. Recalling that a sampling ratio of 20 would limit aliasing erros to less than 1/2 LSB, it may therefore be concluded that video signals up to $(320 \times 10^6/20)$ 16 MHz may be quantized with total errors of less than one LSB.

10.6 SUMMARY

As described previously in this section, the present system is designed to interface with a PDP-11 Computer. However, provisions can be made to interface with other input devices

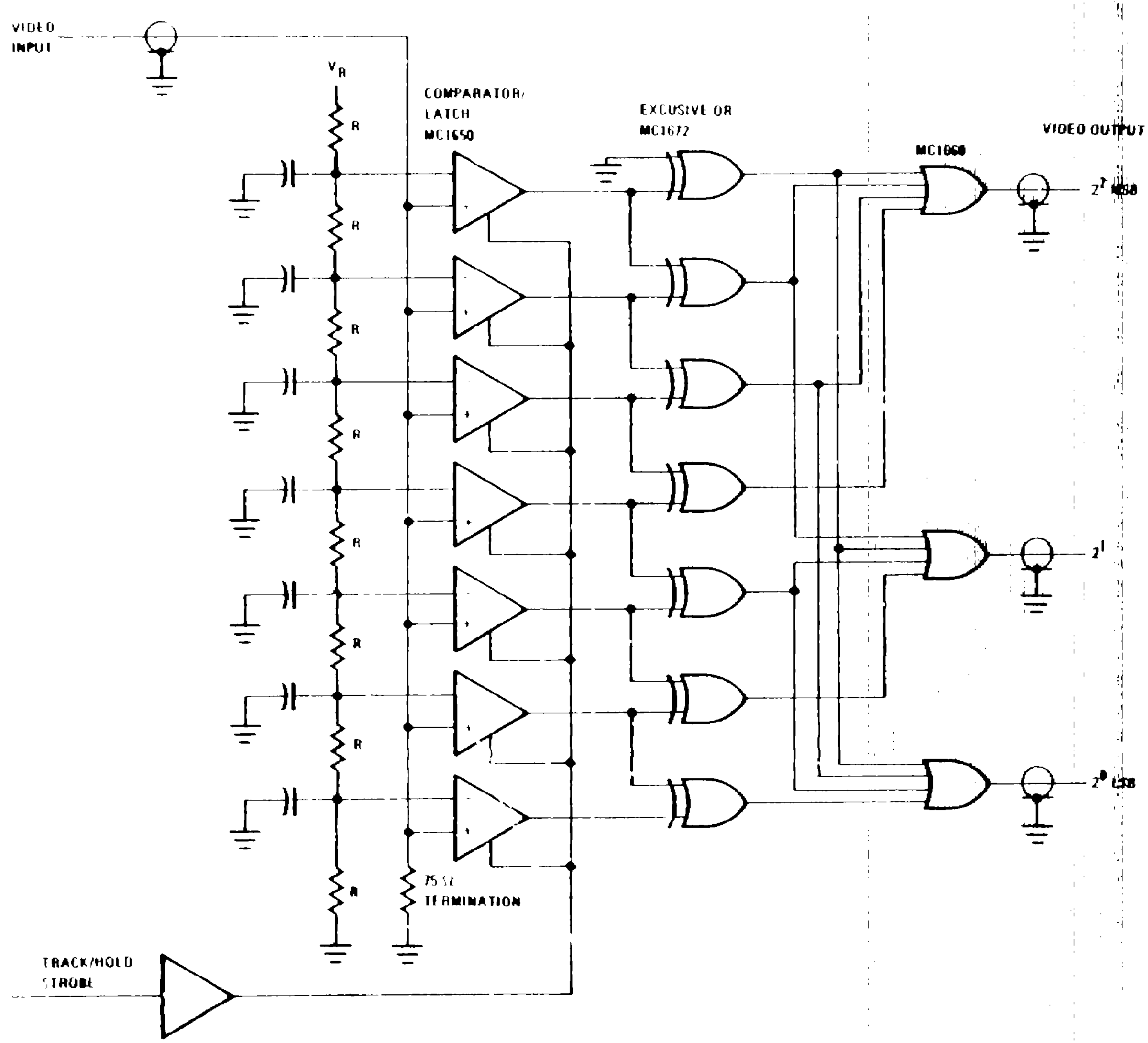


Figure 121 3-Bit Video Digitizer

by adding other input controllers to the input data bus. Other devices which were discussed. for updating the mass memory are:

- Laser scanner
- LLLTV & TV Cameras
- Magnetic Tape recorders
- Video discs

Each device operates at data rates which in most cases require added buffering and formatting to match the input speed requirements of the mass memory.

If data is being stored at random intervals, memory access times of max. 4 to 8 msec must be allowed depending on the scanning speed of the input device.

When a laser scanner is used as an input device with a scanning speed of 60 fields/sec instead of the 180 fields/sec rate of the mass memory display, a 1 megabit random access memory color is recommended to store 1 field of data for input into the mass memory. It is assumed three laser scanners, each with a color primary, are used. This approach updates the mass memory without loss of data and also maintains a maximum scanning speed of the mass memory display. A less expensive approach can be used by decreasing the scanning rate of the mass memory display to the same speed as the scanning rate of the laser scanner. This will however decrease the quality of the display.

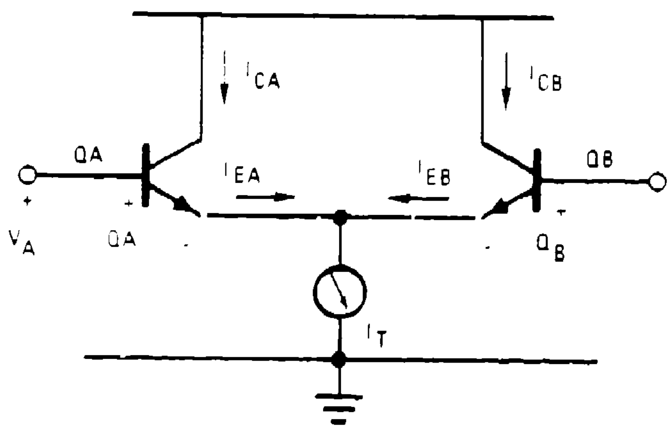
APPENDIX I

CURRENT DIVISION BY AN EMITTER COUPLED PAIR

APPENDIX I

CURRENT DIVISION BY AN EMITTER COUPLED PAIR

Consider the emitter coupled pair QA, QB. It will be assumed the transistors are matched and operate at the same temperature.



The emitter currents are given by

$$I_{EA} = I_S \left[\exp \left(\frac{q\phi a}{kT} \right) - 1 \right]$$

$$I_{EA} = I_S \left[\exp \left(\frac{q\phi a}{kT} \right) - 1 \right]$$

where

- q = electronic charge
- k = Boltzman's constant
- T = junction temperature (absolute)
- ϕ = base to emitter voltage

It will be assumed that ϕ_A and ϕ_B are much larger than $\frac{kT}{q}$. (at room temperature $\frac{kT}{q} \approx 25$ mv).

With this assumption

$$I_{EA} \approx I_S \left[\exp \left(\frac{q\phi a}{kT} \right) \right]$$

$$I_{EA} \approx I_S \left[\exp \left(\frac{q\phi a}{kT} \right) \right]$$

The ratio I_{EA} to I_{EB} is then given by

$$\frac{I_{EA}}{I_{EB}} \left[\exp \frac{q}{kT} \; (\phi a - \phi b) \right] = \left[\exp \frac{q}{kT} \; (V_A - VB) \right]$$

Noting that $I_{EB} = L_T - I_{EA}$ we have

$$\frac{I_{EA}}{L_T - I_{EA}} \approx \left[\exp \frac{q}{kT} \; (V_A - V_B) \right]$$

which gives

$$\frac{I_{EA}}{L_T} = \left[\frac{\exp \frac{q}{kT} (V_A - V_B)}{1 + \exp \frac{q}{kT} \; (V_A - V_B} \right]$$

This ratio is denoted γ, and

$$I_{EA} = \gamma L_T, \qquad I_{EB} = (1-\gamma) \, L_T$$

The factor γ depends on the differential base voltage, $V_A - V_B$, and the temperature.

The collector currents are given by

$$I_{CA} = \alpha I_{EA} = \alpha\gamma I_T$$

$$I_{CB} = \alpha I_{EB} = \alpha(1-\gamma) I_T$$

where

α = the transistor common base forward current transfer ratio.

APPENDIX II

CATHODE RAY TUBE,
DISPLAY PERFORMANCE SPECIFICATION

CATHODE RAY TUBE, DISPLAY PERFORMANCE

SPECIFICATION

3.0 **REQUIREMENTS**

3.1 Description and Intended Use. - The CRT shall be a 5-inch diameter projection, high resolution, high brightness cathode ray tube with a clear, non-browning, ground and polished flat faceplate. The CRT will be used in a prototype experimental model of a 1000 line, 1000 element per line field sequential color television monitor. The field rate for the monitor will be in the range of 150 to 180 fields per second. Modifications to the CRT will be considered when overall system performance can be improved.

3.2 Mechanical. -

3.2.1 Faceplate Requirements. - The thickness, refractive index and dispersion index of the faceplate must be specified by the vendor at the earliest possible date so that they may be included in the optical design calculations.

The surfaces of the faceplate must be flat within .005 inches RMS and be parallel within 0.005 inches.

3.3 Electrical. -

3.3.1 Electrical Design. - An internal spark trap shall be used to minimize potential arcing damage to equipment.

a.	Focusing Method	Magnetic (or electrical if recommended by vendor)
b.	Deflection Method	Magnetic
c.	Heater Voltage	6.3 Volts
d.	Heater Current at 6.3 Volts	0.6 + 10% Ampere (Nominal)
e.	Phosphor (Note 1)	Aluminized special Tri-Color Mix
f.	Overall Length	21 Inches, Maximum

3.3.1 (continued)

g.	Maximum Accelerator Voltage	50,000 Volts
h.	Faceplate Thickness	0.220 ± .030 Inches (Subject to Discussion)
i.	Deflection Angle	46 degrees
j.	Maximum Outside Diameter	5.428 Inches
k.	Minimum Useful Screen Diameter	4 3 4 Inches

3.2.2 Typical Operating Conditions. - Operation shall be as follows:

a.	Accelerator Voltage	40,000 Volts
b.	Grid No. 1 Voltage (Note 2)	-80 to -110 Volts
c.	Line Width (Note 3)	(Typical) 0.003 Inch
d.	Modulation (Note 3)	80 Volts, Maximum
e.	Spot Position (Note 4)	Within a 3 8" radius circle
f.	Light Output (3.1" x 3.1" 1000 line raster)	(Note 5) 10,000 foot-lamberts,
g.	Accelerator Current	Approximately 2000 μA

3.3.3 Operational Notes. - External conductive coating must be grounded.

NOTE:
1. The phosphor to be used is discussed below.
2. Visual extinction of undeflected, focused spot.
3. Measured at minimum specified light output.
4. With the tube shielded against external influences, the underflected and focused spot will fall within a 3 8 inch radius circle concentric with the tube face center.
5. The area brightness is measured using a 15 minute aperture of a Prichard Meter.

3.3.4 Phosphor Requirements. - The subcontractor shall conduct a short research and development program to select a suitable phosphor mix processing the following characteristics:

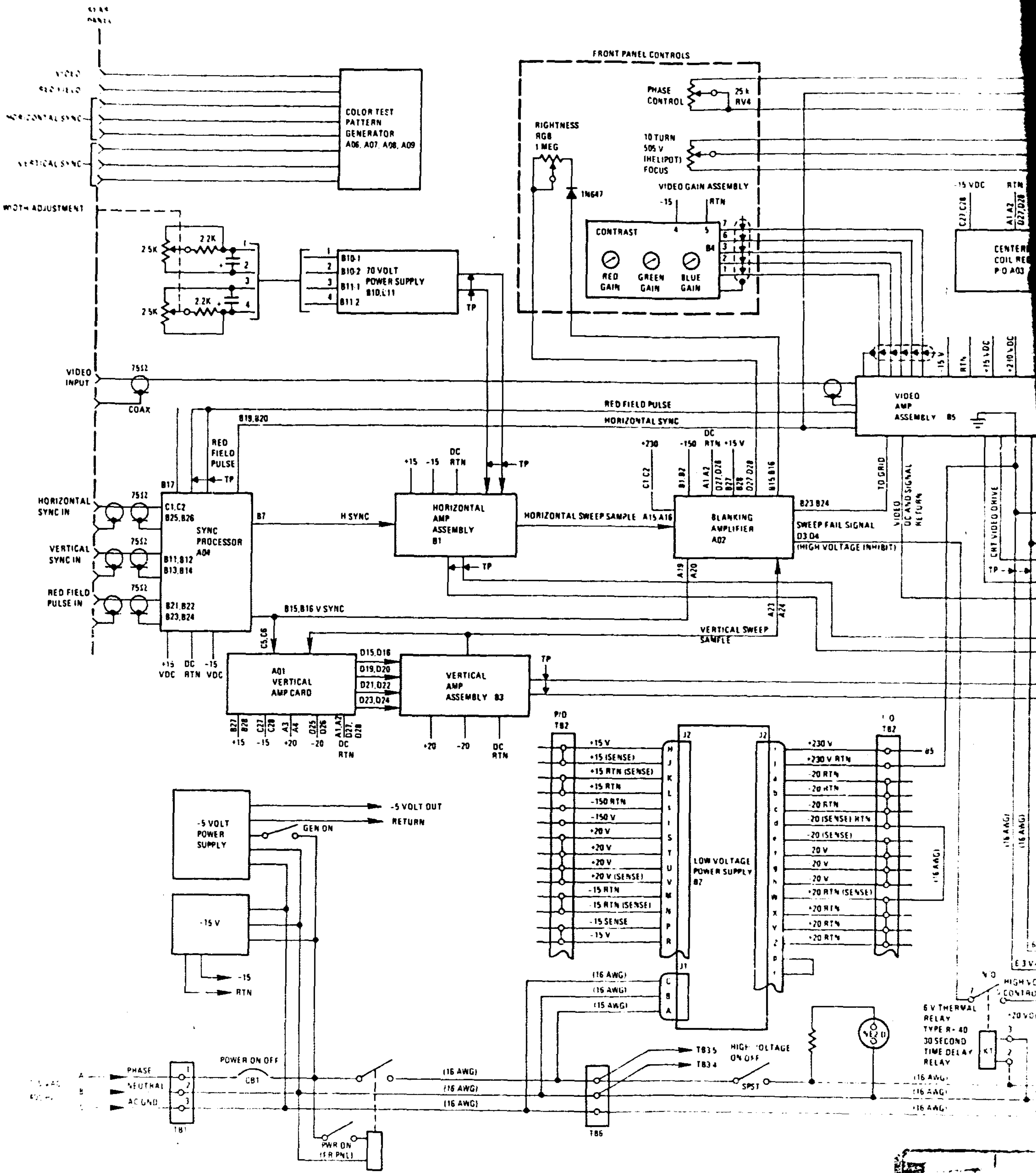
Color	White (Tri-color). The phosphor will be formulated to match field sequential primaries for illuminant C (R, G, B ratio = 0.150: 0.79:0.060*)	
White Brightness	10,000 foot lamberts at writing speed of 290,000 inches per second with simultaneous requirement that line width not exceed 0.003 inches. (Test conditions 3.1" x 3.1" raster, 1000 lines/frame at 180 fields per second).	
Mix*		
Red Phosphor	1500 foot-lamberts	630 Nanometers
Green Phosphor	7900 foot-lamberts	530 Nanometers
Blue Phosphor	600 foot-lamberts	470 Nanometers
Aluminized Screen Desired		
Decay Characteristics (Persistance)		
Red	Down to 1%** within 5.5 ms	
Green	Down to 1%** within 5.5 ms	
Blue	Down to 1%** within 5.5 ms	
Color Linearity	Phosphor response shall be linear with increasing beam current; i.e., the white output shall remain balanced from 0 to 10,000 foot-lamberts.	
Lifetime	With a 20% duty cycle, the desired phosphor lifetime to 50% initial brightness is 2000 hours or more	

* The brightness of the Red, Green and Blue phosphors will be measured through Philco-Ford supplied filters.

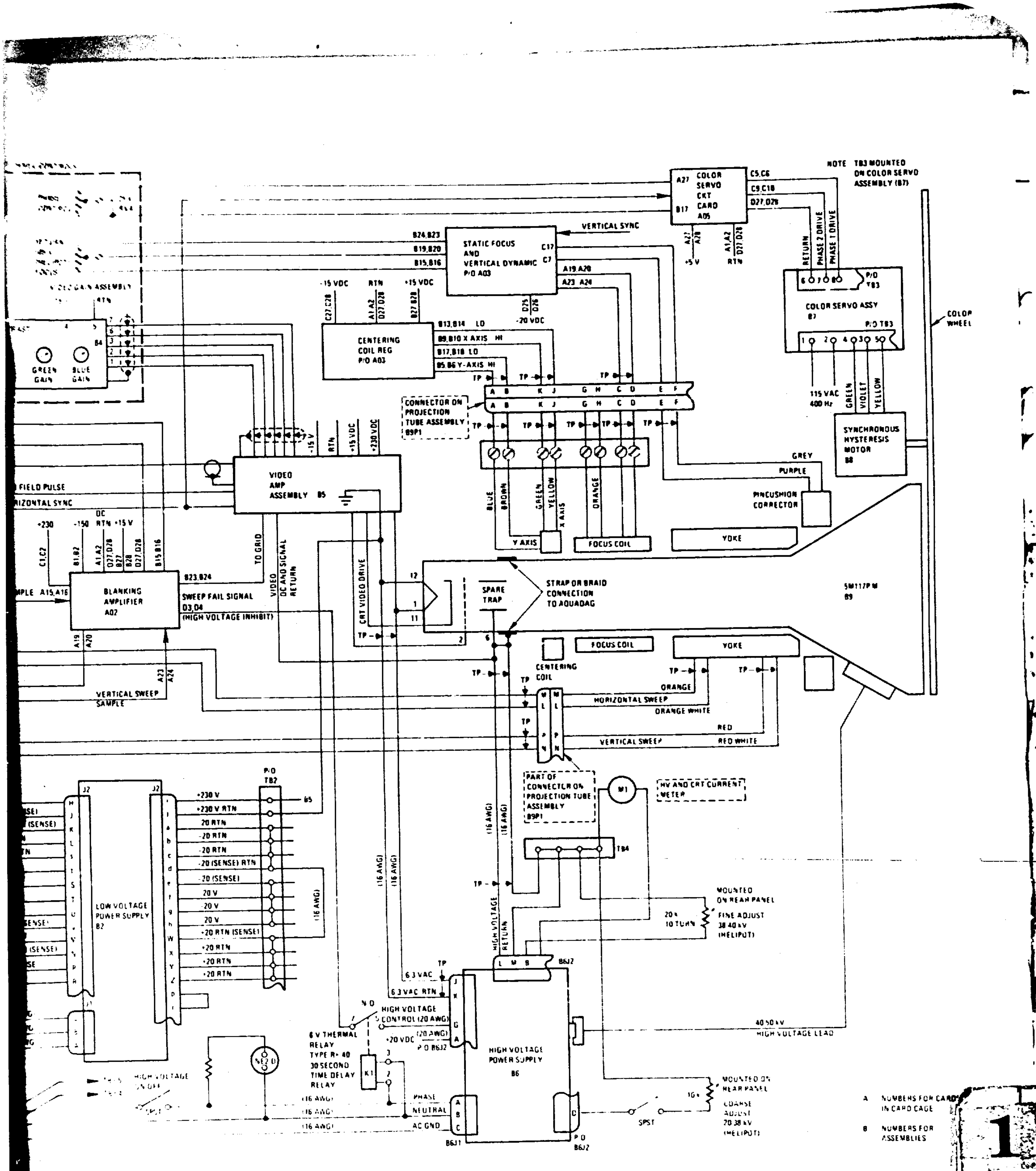
** Phosphors down to = 10% in 5.5 ms may be acceptable if others are not attainable.

APPENDIX III

OVERALL SYSTEM SCHEMATIC


FRONT PANEL CONTROLS
COLOR TEST PATTERN GENERATOR A06, A07, A08, A09
PHASE CONTROL
25 k RV4
RIGHTNESS RG8 1 MEG
1N647
10 TURN 505 V (HELIPOT) FOCUS
VIDEO GAIN ASSEMBLY
CONTRAST
RED GAIN
GREEN GAIN
BLUE GAIN
WIDTH ADJUSTMENT
70 VOLT POWER SUPPLY B10,E11
VIDEO INPUT
COAX
RED FIELD PULSE
HORIZONTAL SYNC
VIDEO AMP ASSEMBLY B5
HORIZONTAL SYNC IN
VERTICAL SYNC IN
RED FIELD PULSE IN
SYNC PROCESSOR A04
H SYNC
HORIZONTAL AMP ASSEMBLY B1
HORIZONTAL SWEEP SAMPLE
BLANKING AMPLIFIER A02
SWEEP FAIL SIGNAL
(HIGH VOLTAGE INHIBIT)
TO GRID
CRT VIDEO DRIVE
B15,B16 V SYNC
VERTICAL SWEEP SAMPLE
A01 VERTICAL AMP CARD
VERTICAL AMP ASSEMBLY B3
-5 VOLT POWER SUPPLY
-5 VOLT OUT
RETURN
GEN ON
LOW VOLTAGE POWER SUPPLY B7
PHASE
NEUTRAL
AC GND
POWER ON OFF
CB1
PWR ON (FR PNL)
HIGH VOLTAGE ON OFF
SPST
6 V THERMAL RELAY TYPE R-40 30 SECOND TIME DELAY RELAY
(16 AWG)

2



Overall System Schematic

APPENDIX IV

COLOR PROGRAM COPY

COLOR3

```
10 REAL X,Y,Z,F,S,R,XT,YT,ZT,XC,YC,ZC,T
20 DIMENSION X(82),Y(82),Z(82),F(82),S(82),R(82)
30 DIMENSION JS(3),KS(3)
40 FILENAME FILTER, SPEC
50 34 DO 5 I=1,81
60 F(I)=0.00
70 S(I)=0.00
80 R(I)=0.00
90 5 CONTINUE
100 PRINT:" SPECTRUM?"
110 READ: SPEC
120 READ(SPEC,84)(JS(I),I=1,2)
130 BEGIN FILE SPEC
140 84 FORMAT(I3,1X,I3)
150 J1=(JS(1)-375)/5
160 K1=(JS(2)-375)/5+1
170 J=J1
180 K=K1
190 READ(SPEC,95)(S(I),I=J1,K1)
200 BEGIN FILE SPEC
210 PRINT:" FILTER?,1,0"
220 READ 96,L
230 IF(L) 45,45,49
240 49 PRINT:" FILTER NAME?"
250 READ: FILTER
260 READ(FILTER,84)(KS(I),I=1,2)
270 J2=(KS(1)-375)/5
280 K2=(KS(2)-375)/5+1
290 L=K2-1
300 READ(FILTER,95)(F(I),I=J2,L)
310 BEGIN FILE FILTER
320 GO TO 50
330 45 DO 10 I=J,K
340 F(I)=1
350 10 CONTINUE
360 50 CONTINUE
370 READ("MIX",81)(X(I),I=1,81)
380 81 FORMAT(4X,F6.4)
390 BEGIN FILE "MIX"
400 READ("MIX",82)(Y(I),I=1,81)
410 82 FORMAT(11X,F6.4)
420 BEGIN FILE "MIX"
430 READ("MIX",83)(Z(I),I=1,81)
440 BEGIN FILE "MIX"
450 83 FORMAT(18X,F6.4)
```

COLOR3 (Contd)

```
460 95 FORMAT(4X,F5.2)
470 96 FORMAT(I3)
480 XT=0
490 YT=0
500 ZT=0
510 JT=J+1
680 DO 20 I=JT,K
690 R(I)=S(I)*F(I)
700 XT=X(I-1)*R(I)+XT
710 YT=Y(I-1)*R(I)+YT
720 ZT=Z(I-1)*R(I)+ZT
730 20 CONTINUE
740 T=XT+YT+ZT
750 PRINT:" YT=",YT
760 XC=XT/T
770 YC=YT/T
780 ZC=ZT/T
790 PRINT 30,XC,YC,ZC
800 30 FORMAT(" XCORR=",F4.3,4X,"YCORR=",F4.3,4X,"ZCORR=",F4.3)
810 WRITE ("ROUT",40)(R(I),I=J,K)
820 40 FORMAT(F5.2)
830 PRINT:" NEW RUN,1,0"
840 READ: M2
850 IF(M2) 33,33,34
860 33 STOP
870 END
```

COLOR3 PROGRAM INSTRUCTIONS

The COLOR3 Program accepts as inputs relative energy spectrum data and filter transmission data. The outputs of the program are the chromaticity coordinates of the spectrum resulting from filter and input spectrum and a quantity "YT" which is proportional to the luminance of that spectrum. The program is written in the Fortran IV computer language.

The program is used by logging onto the GE-615 timesharing system and then calling old program COLOR3. The data for the spectrums and filters must be entered into the computer before running COLOR3.

If data has been entered per instructions below and COLOR3 is loaded, type RUN and supply information when asked for by computer.

Entering Spectrum and Filter Data

Data for either spectrums or filters is entered in format shown below. Minimum wavelength --380nm, maximum wavelength--780nm

380b780	Starting wavelength (b)lank stopping wavelength (b indicates a blank).
380b0.12	
385b0.23	All numbers of this form must enter data in 5nm steps
780b0.41	

Data is read in FORMAT (4x, F4.3).

Notes

The product of a filter and a spectrum specified during a run of COLOR3 can be obtained by the command LIST ROUT. The values printed correspond to the 5nm increments and limits of the input spectrum.

The ideal bandpass filter has 100% transmission in the bandpass, infinitely steep sides and 0% transmission out of band.

XYL

```
10 REAL X2,XR,Y2,YR,L2,LR
15 REAL K1,K2
20 XR=0
21 YR=0
22 X2=0
23 LR=0
24 Y2=0
25 L2=0
26 PRINT: " X1=,Y1=,L1"
27 READ: XR,YR,LR
30 34 PRINT:" X2=,Y2=,L2="
40 READ: X2,Y2,L2
60 K1=(LR/YR)/(LR/YR+L2/Y2)
70 K2=(L2/Y2)/(LR/YR+L2/Y2)
80 XR=K1*XR+K2*X2
90 YR=K1*YR+K2*Y2
95 LR=LR+L2
100 PRINT 31,XR,YR,LR
110 31 FORMAT(" XR=",F4.3," YR==",F4.3," LR=",F8.4)
120 PRINT: " ANOTHER COORDINATE,1,STOP 0"
130 READ: M2
140 IF(M2) 33,33,34
150 33 STOP
160 END
```

XYL INSTRUCTIONS

The XYL program accepts the x, y chromaticity coordinates and the luminances of two colors, and computes the luminance and chromaticity of an additive mixture of the two. The program is written in Fortran IV.

Enter the program, type RUN, and supply information when requested by the computer. After two seets of coordinates have been entered, the program computes the resultant and then requests another coordinate. If zero is entered for stop, the program terminates. If one is entered, then the program requests another set of X2, Y2, L2 data where X2 is the x chromaticity coordinate, X2 is the y chromaticity coordinate and L2 is the luminance.

The new resultant is the additive sum of the previous resultant and the new color. In this way any number of colors can be additively mixed and the chromaticity of the mixture determined.

<u>Input Data Format</u>

The program will print:

X1 = , Y1 = , L1 =

The operator enters the x, y chromaticity coordinates in the format shown:

0.603, 0.343, 100

The suceeding color data are entered with the same formats.

RATIO

```
10 REAL X,Y,XR,YR,XG,YG,XB,YB,FR,FG,FB
15 REAL NUM,DEN
18 PRINT:" SUM COORDINATES,X,Y"
19 READ: X,Y
20 PRINT:" XR=,YR="
21 READ: XR,YR
22 PRINT:" XG=,YG="
23 READ: XG,YG
24 PRINT:" XB=,YB="
25 READ: XB,YB
40 D=(XR*(YG-YB)+XG*(YB-YR)+XB*(YR-YG))*Y
50 FR=(YR/D)*(X*(YG-YB)+XG*(YB-Y)+XB*(Y-YG))
60 FG=(YG/D)*(XR*(Y-YB)+X*(YB-YR)+XB*(YR-Y))
70 FB=(YB/D)*(XR*(YG-Y)+XG*(Y-YR)+X*(YR-YG))
80 PRINT 31,FR,FG,FB
90 31 FORMAT( " YR/Y=",F5.3," YG/Y=",F5.3," YB/Y=",F5.3)
95 PRINT:" NORMALIZING FACTOR,NUMERATOR,DENOM"
96 READ: NUM,DEN
100 FR= FR*(NUM/DEN)
110 FG=FG*(NUM/DEN)
120 FB=FB*(NUM/DEN)
130 PRINT:" RATIOS,RED, GREEN, BLUE"
140 PRINT: FR,FG,FB
150 END
```

RATIO INSTRUCTIONS

Ratio is a Fortran IV program which calculates the ratios of the luminances of three known primaries required to match a specified set of chromaticity coordinates.

To use the program, enter the program statements into the computer, type RUN, and supply the data requested by the computer.

Input Data Formats

The program will print:

XR = , YR =

The red chromaticity coordinates are supplied:

0.636, 0.343

The other coordinates are inputted in the same format when requested.

The output is printed:

$$\frac{Y_R}{Y} = XXX, \quad \frac{Y_G}{Y} = XXX, \quad \frac{Y_B}{Y} = XXX$$

where Y_R Y is the ratio of the required red luminance to Y, the total luminance of the three primaries added together.

The program then prints:

NORMALIZING FACTOR, NUMERATOR, DENOM

This factor is entered in sequence: numerator, then denominator. For example, if we wanted to normalize the ratio of the Y_G Y to find the number of green footlamberts to match 400 footlamberts of the resultant we would enter:

400, 1

And the program will print out:

RATIOS, RED, GREEN, BLUE

Where each printed quantity is a new number

$$\frac{Y_R}{Y} \times \frac{NUM}{DENOM} \quad \frac{Y_G}{Y} \times \frac{NUM}{DENOM} \quad \frac{Y_B}{Y} \times \frac{NUM}{DENOM}$$

ADDER

```
20 REAL X,Y,Z,F,S,R,XT,YT,ZT,XC,YC,ZC,T
30 DIMENSION X(82),Y(82),Z(82),F(82),S(82),R(82)
32 DIMENSION NO(82)
40 DIMENSION JS(3),KS(3)
50 FILENAME FILTER, SPEC
60 DO 5 I=1,81
70 F(I)=0,00
80 S(I)=0,00
90 R(I)=0,00
100 5 CONTINUE
101 34 PRINT:" SPECTRUM?"
102 READ: SPEC
110 READ(SPEC,84)(JS(I),I=1,2)
111 BEGIN FILE SPEC
130 84 FORMAT(I3,1X,I3)
140 J1=(JS(1)-375)/5
150 K1=(JS(2)-375)/5+1
160 J=J1
170 K=K1
180 READ(SPEC,95)(S(I),I=J1,K1)
185 BEGIN FILE SPEC
190 PRINT:" MULTIPLYING FACTOR"
195 READ: W
320 JT=J+1
330 DO 24 I=JT,K
340 R(I)=R(I)+S(I)*W
350 24 CONTINUE
360 DO 29 I=1,81
370 S(I)=0,00
380 29 CONTINUE
510 95 FORMAT(4X,F5,2)
711 PRINT:" NEW RUN,TYPE 1,STOP,TYPE 0"
712 READ: M2
713 IF(M2) 33,33,34
720 33 DO 31 I=1,81
725 NO(I)=380+5*(I-1)
730 31 CONTINUE
740 WRITE("ADD",40)(NO(I-1),R(I),I=2,82)
745 40 FORMAT(I3,1X,F5.2)
755 END
```

ADDER INSTRUCTIONS

ADDER is a Fortran IV program which is essentially a modification of the program COLOR3. The program permits the point by point addition of any number of phosphor or filter spectra where the values of the spectra are specified at 5 nanometer intervals over the range from 380 to 780 nanometers. The spectra to be added together must be inputted to a file with the data format specified in for COLOR3 data. The spectra data is then given a name and stored in the program working area of the computer so that it can be accessed by the ADDER program.

Input Data Format

The program will print: SPECTRUM

The user then types the file name of the previously stored spectrum data.

Example: GSPEC

The program then will print: MULTIPLYING FACTOR

The user inputs a multiplying factor.

Example: 10.4

The spectrum GSPEC is now only multiplied by 10.4 at every data point.

The program then types: NEW RUN, TYPE 1, STOP, TYPE 0

If one wants only to scale the GSPEC, he types 0 and the new data will be written in to a temporary file named ADD and the run terminated. Later, the temporary file ADD can be stored by performing a permanent command under a new file name.

If 1 is entered, the program again types: SPECTRUM

The user types the file name of another spectrum data file.

Example: RSPEC

The program prints: MULTIPLYING FACTOR

The user inputs a multiplying factor.

Example: 5.0

The program again asks if it should continue or stop.

Any number of spectra can be added with any multiplying factor for each spectrum. Again, when 0 is specified for stop, the sum of the spectra is written into the temporary output file ADD, and the program terminates. This file can be made permanent as noted above. The data saved for the above example would be:

10.4 x GSPEC - 5 x RSPEC = ADD

SHIFT

```
10 DIMENSION JS(2),N(82),S(82)
20 FILENAME OLD
30 PRINT:" FILENAME?"
40 READ: OLD
50 READ(OLD,11) JS(1),JS(2)
60 PRINT:" OLD LIMITS"
70 PRINT: JS(1),JS(2)
80 PRINT:" DESIRED SHIL+FT,+ OR-    NM"
90 READ: K
100 11 FORMAT(I3,1X,I3)
110 JS(1)=JS(1)+K
120 JS(2)=JS(2)+K
130 J1=(JS(1)-375)/5
140 K1=(JS(2)-375)/5
150 READ(OLD,12)(N(I),S(I),I=J1,K1)
160 12 FORMAT(I3,1X,F4.2)
161 DO 25 I=J1,K1
162 N(I)=N(I)+K
163 25 CONTINUE
170 WRITE("RSHIFT",41) JS(1),JS(2)
180 WRITE("RSHIFT",42)(N(I),S(I),I=J1,K1)
185 PRINT:" OUTFILE NAME=RSHIFT"
190 41 FORMAT(I3,1X,I3)
200 42 FORMAT(I3,1X,F4.2)
210 END
```

SHIFT INSTRUCTIONS

SHIFT is a Fortran IV program which permits a previously inputted filter spectrum to be shifted any specified number of nanometers toward the longer wavelengths (+) or toward the shorter wave lengths (-). The filter shape and bandwidth are preserved as the filter is shifted.

Input Data Formats

The program will print: FILE NAME?

The user then enters the file name of a previously saved filter spectrum.

Example: BAUGRN

The program then prints: DESIRED SHIFT, + OR - NM

The user then specified a shift which is an integer and is a multiple of 5 nanometers, such as 5, 10, 15 nm, etc.

Example: 30

The computer then prints: OUTFILE NAME = RSHIFT

This indicates that a new temporary file with the name RSHIFT has been created containing the shifted filter data. This temporary file must be changed to a permanent file and given a new name before the program is used again for other data. If this is not done, the next run of shift will chain more data onto the file RSHIFT and this new data will be inaccessible.

MIX

This data is the values of the $\bar{x}$, $\bar{y}$, $\bar{z}$ distribution coefficients at 5 nanometer intervals. This data must be entered and given the file name "MIX" to use the program COLOR3.

MIX

380	0,0014	0,0000	0,0065
385	0,0022	0,0001	0.0105
390	0,0042	0,0001	0,0201
395	0,0076	0,0002	0,0362
400	0,0143	0,0004	0,0679
405	0,0232	0,0006	0,1102
410	0,0435	0,0012	0,2074
415	0,0776	0,0022	0.3713
420	0,1344	0,0040	0.6456
425	0,2148	0,0073	1,0391
430	0.2839	0.0116	1.3856
435	0.3285	0,0168	1.6230
440	0.3483	0.0230	1.7471
445	0,3481	0,0298	1.7826
450	0,3362	0,0380	1,7721
455	0.3187	0,0480	1.7441
460	0,2908	0,0600	1,6692
465	0,2511	0.0739	1.5281
470	0.1954	0,0910	1.2876
475	0.1421	0.1126	1,0419
480	0.0956	0,1390	0,8130
485	0,0580	0,1693	0,6162
490	0.0320	0,2080	0,4652
495	0.0147	0,2586	0,3533
500	0,0049	0.3230	0,2720
505	0,0024	0,4073	0,2123
510	0,0093	0,5030	0,1582
515	0.0291	0,6082	0.1117
520	0.0633	0,7100	0,0782
525	0.1096	0,7932	0,0573
530	0,1655	0,8620	0.0422
535	0,2257	0,9149	0.0298
540	0,2904	0,9540	0,0203
545	0,3597	0,9803	0,0134
550	0.4334	0,9950	0,0087
555	0.5121	1,0002	0,0057
560	0.5945	0,9950	0.0039
565	0,6784	0,9786	0.0027
570	0.7621	0,9520	0,0021
575	0.8425	0,9154	0,0018
580	0.9163	0,8700	0,0017
585	0.9786	0,8163	0,0014
590	1.0263	0,7570	0,0011
595	1,0567	0,6949	0,0010
600	1,0622	0,6310	0,0008
605	1,0456	0.5668	0,0006

MIX (Contd)

610	1.0026	0.5030	0.0003
615	0.9384	0.4412	0.0002
620	0.8544	0.3810	0.0002
625	0.7514	0.3210	0.0001
630	0.6424	0.2650	0.0000
635	0.5419	0.2170	0.0000
640	0.4479	0.1750	0.0000
645	0.3608	0.1382	0.0000
650	0.2835	0.1070	0.0000
655	0.2187	0.0816	0.0000
660	0.1649	0.0610	0.0000
665	0.1212	0.0446	0.0000
670	0.0874	0.0320	0.0000
675	0.0636	0.0232	0.0000
680	0.0468	0.0170	0.0000
685	0.0329	0.0119	0.0000
690	0.0227	0.0082	0.0000
695	0.0158	0.0057	0.0000
700	0.0114	0.0041	0.0000
705	0.0081	0.0029	0.0000
710	0.0058	0.0021	0.0000
715	0.0041	0.0015	0.0000
720	0.0029	0.0010	0.0000
725	0.0020	0.0007	0.0000
730	0.0014	0.0005	0.0000
735	0.0010	0.0004	0.0000
740	0.0007	0.0003	0.0000
745	0.0005	0.0002	0.0000
750	0.0003	0.0001	0.0000
755	0.0002	0.0001	0.0000
760	0.0002	0.0001	0.0000
765	0.0001	0.0000	0.0000
770	0.0001	0.0000	0.0000
775	0.0000	0.0000	0.0000
780	0.0000	0.0000	0.0000

GSPEC

GSPEC and RSPEC are the green phosphor and the red phosphor spectrum data used in specifying the color wheel filters and the CRT phosphor ratios for the proper performance.

GSPEC

545 550
545 1.00
550 0.11

RSPEC

540 630
540 0.05
545 0.00
550 0.00
555 0.00
560 0.00
565 0.00
570 0.00
575 0.00
580 0.00
585 0.00
590 0.00
595 0.25
600 0.00
605 0.00
610 0.00
615 0.27
620 0.15
625 1.00
630 0.29

APPENDIX V

LENS ACCEPTANCE TEST REPORT

[redacted]

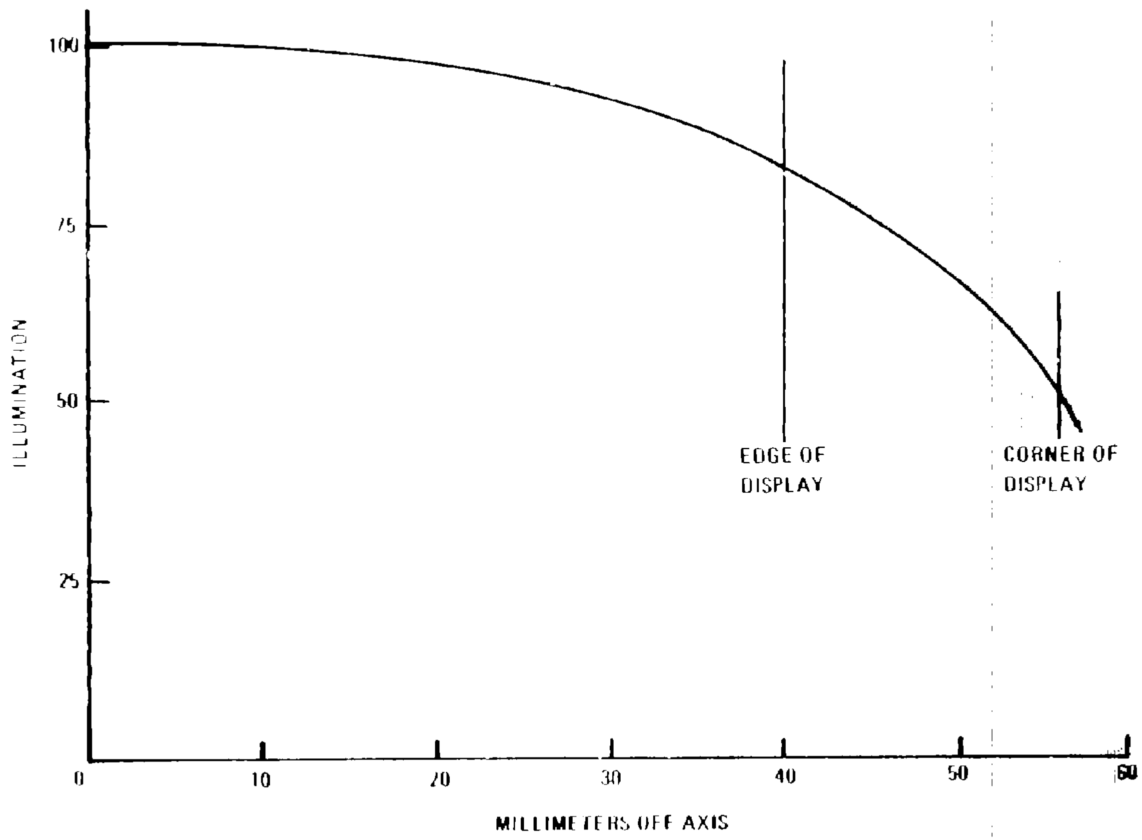
LENS ACCEPTANCE TEST REPORT

DATA SHEET

PAR.	REQUIREMENTS	NOMINAL	TOL.	MEAS.
7.1	OBJECT SIZE	80 MM x 80 MM	(NOM)	80 x 80
7.2	IMAGE SIZE	356 MM x 356 MM	(NOM)	356 x 356
7.3	RESOLUTION	13TV LINES @ 50% MTF	(MIN)	See MTF curves
7.4	TRACK LENGTH	950 MM ±50 MM	(NOM)	950 MM
7.5	APERTURE (F NO.)	1.0	(NOM)	1.0 by design
7.6	FIELD	FLAT		
7.6	FIELD	FLAT	(NOM)	See MTF curves
7.7	DISTORTION	1% MAX PINCUSHION, OR 5% MAX BARREL	(MAX)	-1.2% by design
7.8	AXIAL TRANSMISSION	70% WITH A GOAL OF 80%	(MIN)	76%
7.9	AXIAL TRANSMISSION (OPTIONAL)	SAME AS 7.8	(MIN)	76%
7.10	RELATIVE ILLUMINATION	70% UP TO 40 MM RADIUS OFF -AXIS WITH BEST EFFORT FOR 70% FROM 40 MM RADIUS TO CORNER.	(MIN)	83% @ 40 MM

WITNESSED BY:
(PHILCO-FORD)

INSPECTED BY:
(DIFFRACTION OPTICS)



Relative Illumination

DISTRIBUTION LIST

OFFICE OF THE SECRETARY OF THE AIR FORCE	NO. OF COPIES
Office of the Director of Defense Research and Engineering ATTN: Mr. R. Spellman Washington, DC 20330	1
HEADQUARTERS UNITED STATES AIR FORCE	
AFSC(SDR) Andrews AFB Washington, DC 20331	1
Director of Laboratories (DL) Andrews AFB Washington, DC 20331	1
Hq USAF(SAMID) Washington, DC 20330	1
Hq USAF(XO) Washington, DC 20330	1
AUL (Document Librarian) Maxwell AFB, AL 36112	1
AFCRL (Electronics Research Library) L. G. Hanscom Field Bedford, MA 01730	1
Langley Research Center (NASA) ATTN: Librarian Langley Field, VA 23365	1
RADC Mr. Hicks (INRA) Griffiss AFB, NY 13442	1
RADC(ISCE) Robert LaSalle Griffiss AFB, NY 13442	1

ARMY	NO. OF COPIES
Commanding General, Combat Surveillance and Avionics Dept. ATTN: Electro-Optical Group U.S. Army Electronics Proving Ground Ft. Huachuca, AZ 85613	1
U.S. Army Electronics R&D Laboratory ATTN: SELRA/OMSEL-RD-PRG Ft. Monmouth, NJ 07703	1
Commanding General U.S. Army Electronics Command ATTN: AMSEL-NLAI (Mr. S. F. LaForgia) Ft. Monmouth, NJ 07703	1
NAVY	
Chief, Bureau of Naval Weapons (FFRD-11) Washington, DC 20323	1
Chief of Naval Research Navy Department Washington, DC 20360	1
Commander Naval Air Systems Command Headquarters (AIR-604) Washington, DC 20360	1
Commanding Officer Naval Air Development Center Johnsville Warminster, PA 18974	1
Commanding Officer Naval Avionics Facility 21st and Arlington Avenues Indianapolis, IN 46218	1
OTHER ACTIVITIES	
NASA Scientific & Technical Info Facility ATTN: NASA Representative (S-AK DL) P. O. Box 33 College Park, MD 20740	2

OTHER ACTIVITIES (Continued)	NO. OF COPIES
Defense Documentation Center (TISIA) Cameron Station Alexandria, VA 22314	2
Defense Intelligence Agency ATTN: DIARD Washington, DC 20305	1
NAVAIR (Mr. Leo B. Packard) Reconnaissance and Technical Support Area 4301 Suitland Road Washington, DC 20390	1

ACTIVITIES AT WPAFB, OH 45433

ATTN: AFAL/RSP/Mr. D. B. Learish	30
4950/1	1
2750 ABW/SSL	1

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Philco-Ford Corporation 3939 Fabian Way Palo Alto, California 94303	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Real-Time Improved Color Image Display

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Eleazar W. Morales	Rodney K. Toone	Jonathan Roeloffs
Alan deSchweinitz	Bryan E. Loucks	Larry T. Shoenberger
Frederick T. Buhler	Harold M. Austefjord	Michael B. Farbett

6. REPORT DATE May 1, 1972	7a. TOTAL NO. OF PAGES 283	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO. F33615-70-C-1417 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) WDL-TR4861 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

Distribution limited to US Government Agencies only, because this report covers test and evaluation of commercial products Apr 1972. Other requests for this document must be made through AFAL (RSP), Wright-Patterson AFB, OH 45433.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Avionics Laboratory

13. ABSTRACT

The work covered in this report was intended to explore preliminary designs and hardware implementation which would yield results to eventually provide a satisfactory design for a real-time improve color display.

The fundamental concept used in this work is not new. The sequential color approach used was first introduced by CBS over 30 years ago. The uniqueness of this approach involves the use of this concept along with projection optics to achieve significant advances in the display area of high resolution, color purity, and brightness while inherently having perfect registration.

The display development included the achievement of significant advances in the areas of optical design, CRT phosphor, specialized deflection, and video circuit designs. This report summarizes the results of these developments and subsequent evalutaion. Information was derived, as a result of the test bed that was developed, which outlines a design capable of possible utilization as an airborne color display.

DD FORM 1473

UNCLASSIFIED
Security Classification

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
DISPLAY, COLOR						
DISPLAY, PROJECTION CRT						
PROJECTION LENS						
FILTER WHEEL, TRI COLOR						
FIELD SEQUENTIAL						
HIGH RESOLUTION COLOR						
COMPUTER INTERFACE						
MASS MEMORY						

INSTRUCTIONS TO FILL OUT DD FORM 1473 - DOCUMENT CONTROL DATA
(See ASPR 4-211)

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD directive 5200.10 and Armed Forces Industrial Security Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of the author(s) in normal order, e.g., full first name, middle initial, last name. If military, show grade and branch of service. The name of the principal author is a minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, and 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, task area number, systems numbers, work unit number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. DISTRIBUTION STATEMENT: Enter the one distribution statement pertaining to the report.

Contractor-Imposed Distribution Statement

The Armed Services Procurement Regulations *(ASPR), para 9-203* stipulates that each piece of data to which limited rights are to be asserted must be marked with the following legend:

"Furnished under United States Government Contract No.________. Shall not be either released outside the Government, or used, duplicated, or disclosed in whole or in part for manufacture or procurement, without the written permission of __________, except for: (i) emergency repair or overhaul work by or for the Government, where the item or process concerned is not otherwise reasonably available to enable timely performance of the work, or (ii) release to a foreign government, as the interests of the United States may require; provided that in either case the release, use, duplication or disclosure hereof shall be subject to the foregoing limitations. This legend shall be marked on any reproduction hereof in whole or in part."

If the above statement is to be used on this form, enter the following abbreviated statement:

"Furnished under U. S. Government Contract No.______. Shall not be either released outside the Government, or used, duplicated, or disclosed in whole or in part for manufacture or procurement, without the written permission of_________, per ASPR 9-203."

DoD Imposed Distribution Statements *(reference DoD Directive 5200.20)* "Distribution Statements *(Other than Security)* on Technical Documents," March 29, 1965.

STATEMENT NO. 1 - Distribution of this document is unlimited.

STATEMENT NO. 2 (UNCLASSIFIED document) - This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of *(fill in controlling DoD office)*.

(CLASSIFIED document) - In addition to security requirements which must be met, this document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval *(fill in controlling DoD Office)*.

STATEMENT NO. 3 (UNCLASSIFIED document) - Each transmittal of this document outside the agencies of the U. S. Government must have prior approval of *(fill in controlling DoD Office)*.

(CLASSIFIED document) - In addition to security requirements which apply to this document and must be met, each transmittal outside the agencies of the U. S. Government must have prior approval of *(fill in controlling DoD Office)*.

STATEMENT NO. 4 (UNCLASSIFIED document) - Each transmittal of this document outside the Department of Defense must have prior approval of *(fill in controlling DoD Office)*.

(CLASSIFIED document) - In addition to security requirements which apply to this document and must be met, each transmittal outside the Department of Defense must have prior approval of *(fill in controlling DoD Office)*.

STATEMENT NO. 5 (UNCLASSIFIED document) - This document may be further distributed by any holder only with specific prior approval of *(fill in controlling DoD Office)*.

(CLASSIFIED document) - In addition to security requirements which apply to this document and must be met, it may be further distributed by the holder ONLY with specific prior approval of *(fill in controlling DoD Office)*.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

☆ U.S. GOVERNMENT PRINTING OFFICE : 1966 O—226-690